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CONTENTS

AN EDUCATIONAL STUDY OF AMPLITUDE MODULATION CIRCUITS USING MATHEMATICAL MODELING AND LABORATORY EXPERIMENTS

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Abstract: This paper presents a comprehensive analysis of an amplitude modulation (AM) circuit based on mathematical modeling, MATLAB-based simulation, and laboratory measurements. An analytical model of the AM modulation process is first developed to describe the circuit behavior under ideal and non-ideal operating conditions. The proposed model is then implemented in MATLAB to evaluate key performance characteristics, including modulation index, spectral components, and signal distortion. To validate the theoretical and simulation results, an experimental AM modulation circuit is implemented and tested in a laboratory environment. Measured results are compared with analytical predictions and simulation outcomes, demonstrating good agreement across different operating conditions. The combined use of mathematical analysis, simulation, and experimental validation provides a robust framework for understanding AM circuit performance and highlights the effectiveness of MATLAB-based tools in supporting circuit analysis and verification.

Key words: amplitude modulation (AM), signal spectrum analysis, experimental validation, analog communication systems.

1. ANALYSIS OF EDUCATIONAL APPROACHES TO AMPLITUDE MODULATION

Educational investigations of amplitude modulation commonly employ three methodological approaches: analytical modeling, simulation-based analysis, and laboratory experimentation. Each approach contributes distinct insights into AM

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behavior; however, each is subject to specific constraints that influence its effectiveness and scope [1], [5], [8].

Analytical modeling enables the formal derivation of AM signal expressions and provides insight into spectral properties, modulation index behavior, and ideal system performance. This approach is essential for establishing a theoretical reference against which other methods may be evaluated. Essentially idealized assumptions are used to construct analytical models, which do not account for non-linearities, noise, or component tolerances. The method offers little information about the impact of implementation. When implemented without corrective modeling, quantitative findings may differ from real-world realizations [2], [9].

Simulation environments, such as MATLAB or Simulink, facilitate numerical evaluation of AM systems under controlled conditions. Parameter sensitivity analysis and frequency-domain inspection can be performed efficiently, enabling systematic investigation beyond analytical tractability. The accuracy of the underlying models sets a limit on simulation fidelity. If hardware-dependent events are not clearly modeled, numerical results may obscure them. An over-reliance on simulation could make it harder to critically assess real-world limitations.

Experimental investigation provides empirical validation of AM circuit behavior and captures non-ideal effects inherent in physical implementations. Measurement data enable direct assessment of discrepancies between theoretical predictions and actual system performance. Environmental variables and instrument accuracy may have an impact on experimental reproducibility. The range of possible operating circumstances is limited by hardware limitations. Measurement noise and setup variability might affect how data is interpreted.

Comparative analysis indicates that each approach addresses a distinct dimension of AM system characterization. Analytical modeling offers theoretical baselines, simulations enable parametric exploration, and experiments provide empirical validation. However, the independent application of any single approach yields an incomplete characterization of AM behavior. An integrated analytical–simulation–experimental methodology reduces methodological bias and enhances result reliability. By cross-validating outcomes across multiple domains, this combined framework supports a more rigorous and comprehensive evaluation of amplitude modulation systems in an educational context.

The circuit diagram from figure 1, shows the experimental and analytical framework used to implement and evaluate an amplitude modulation (AM) circuit based on an analog multiplier (AD633). The system is composed of three main functional stages: signal generation, modulation, and observation.

A low-frequency modulating signal is generated with a tunable frequency range of approximately 1 kHz to 50 kHz. This signal represents the baseband information to be transmitted. In parallel, a high-frequency carrier signal is generated with a frequency range between 200 kHz and 700 kHz, consistent with standard AM operation conditions [3], [7].

Both signals are applied to the input ports of the AD633 analog multiplier, which performs real-time signal multiplication. The AD633 internally scales the product of the input signals and provides a summed output stage, enabling the realization of

conventional amplitude modulation. By appropriate biasing and scaling, the output corresponds to a standard AM waveform in which the carrier amplitude is varied according to the modulating signal [4], [6].

The implementation is based on AD 633, analog multiplier (used for modulation/demodulation, phase detection, as voltage-controlled amplifier/attenuator/filter). The multiplier operates from dual-polarity power supplies ranging from ± 8 V to ± 18 V (inputs should stay within roughly ± 10 V to avoid clipping.) and with a nominal output voltage of 10 V full scale (provided by a buried Zener reference). For more detailed technical information, including pin configurations and performance characteristics, you can refer to the official AD633 datasheet (Analog Devices).
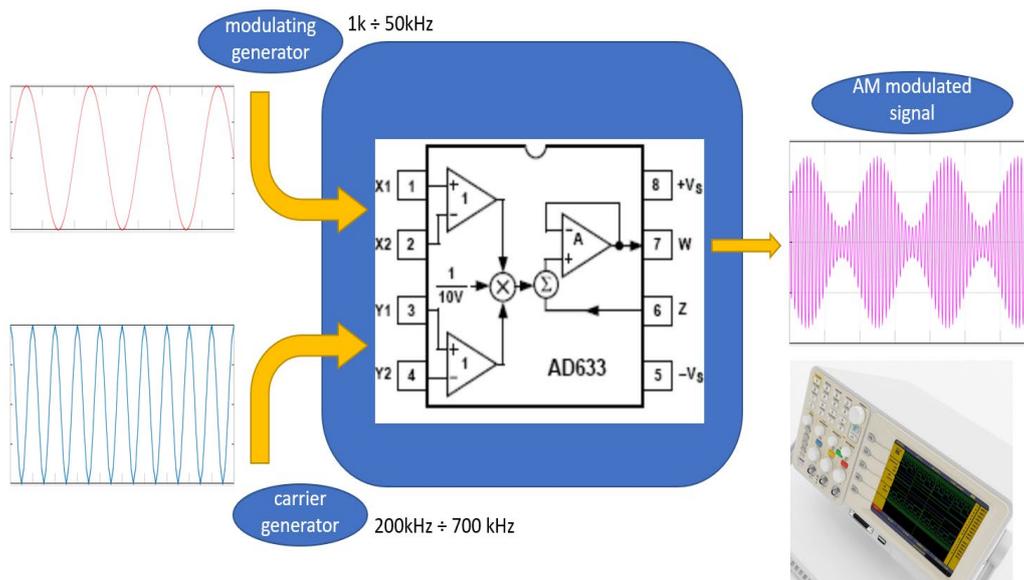
Fig.1. UML Block Diagram using SysML-style blocks, which is the correct UML family for engineering systems like protection relays of most common interdependencies

The AD633 is commonly used for AM modulation. It multiplies two analog input voltages and provides a scaled output: W = (X+Y)/10 + Z

For the duration of the whole exercise the panel B (AM modulation) has to be supplied with a modulating signal and carrier signal, by using cables of suitable length and of such color to make easier the control of the connections.

The resulting AM-modulated signal is observed at the output using laboratory measurement equipment (e.g., digital oscilloscope), allowing time-domain visualization of the modulated waveform and indirect verification of modulation depth, envelope shape, and signal integrity [10].

This schematic supports both analytical modeling and experimental validation, making it suitable for systematic comparison between theoretical predictions, MATLAB-based simulations, and physical measurements.

2. MATHEMATICAL MODEL OF THE AM MODULATION CIRCUIT

2.1 Mathematical Model implementation

The amplitude modulation process implemented in the proposed system is based on the multiplication of a low-frequency modulating signal with a high-frequency carrier signal using an analog multiplier (AD633).
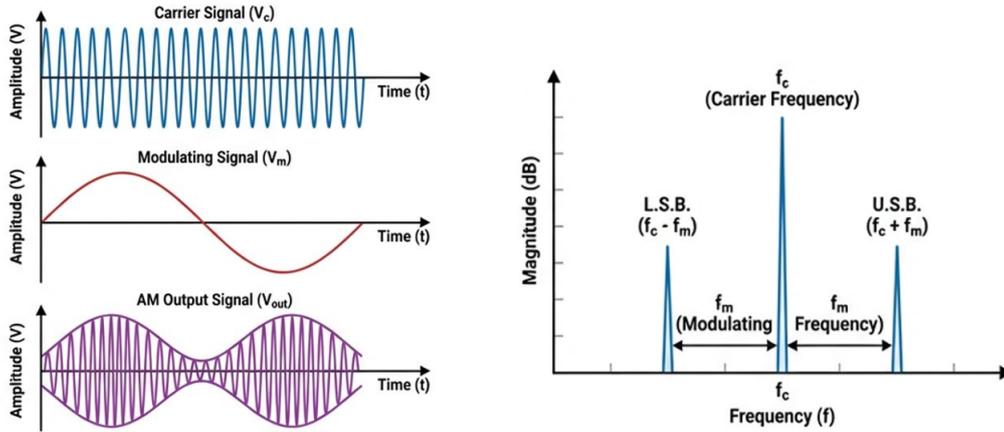
Fig.2. Experimental study of AM modulation: a) time domain waveforms; b) frequency spectrum

The modulating signal is modeled as a sinusoidal waveform:

$$m(t) = A_m cos(2\pi f_m t) \qquad (1)$$

Where A_m is the amplitude of the modulating signal and f_m is the modulating frequency (1kHz, 50kHz).

The carrier signal is defined as:

$$c(t) = A_c cos(2\pi f_m t) \qquad (2)$$

Where A_c is the carrier amplitude and f_m is the carrier frequency (200kHz,700kHz).

The AD633 performs analog multiplication according to the relationship:

$$v_0(t) = \frac{(x_1 - x_2)(y_1 - y_2)}{10} \qquad (3)$$

the output voltage becomes:

$$v_0(t) = A_c[1 + \mu cos(2\pi f_m t)]cos(2\pi f_c t) \qquad (4)$$

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2.2. Modulation circuit analysis

This next figure illustrates a circuit for the Amplitude Modulator (AM) using a general-purpose analog multiplier integrated circuit (IC) such as the MC1496 or AD633.
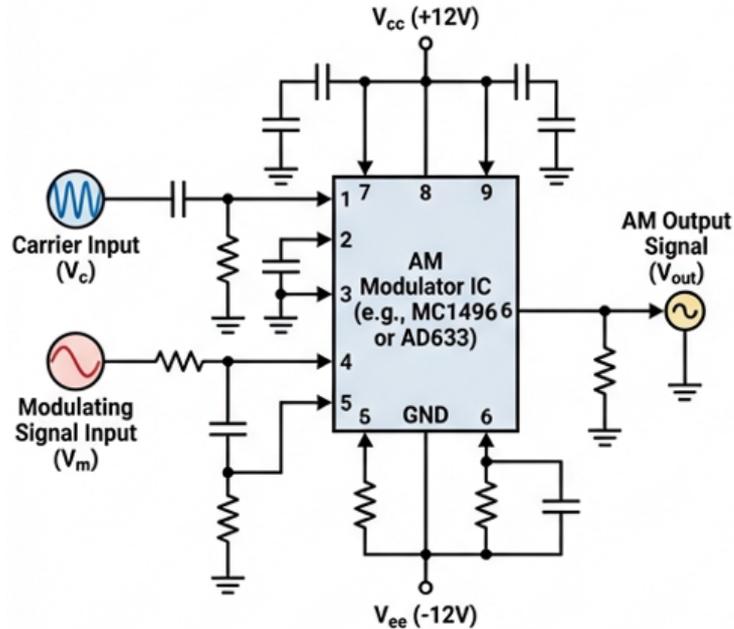
Fig.3. Experimental circuit diagram of the AM modulator

The amplitude modulation circuit's purpose is to combine a high-frequency carrier signal (Vc) with a lower-frequency modulating signal (Vm), which contains the information, e.g., audio) to produce an Amplitude Modulated (AM) output signal (Vout).

3. THE MODEL FOR EXPERIMENTAL ANALISYS OF THE AMPLITUDE MODULATION CIRCUIT

Figure 4 shows the effect of overmodulation on an AM (Amplitude Modulation) signal by displaying three separate time-domain waveforms, each corresponding to a different modulation index (m). The modulation index is the ratio of the amplitude of the modulating signal to the amplitude of the carrier signal. The amplitude of the high-frequency carrier wave varies in accordance with the lower-frequency modulating signal, but the carrier amplitude never reaches zero. The signal envelope (the outline of the peaks of the carrier wave) perfectly follows the shape of the original modulating signal without any distortion, ensuring high fidelity upon demodulation.

Overmodulation causes severe distortion of the signal, which results in a garbled or unintelligible message when received by a standard AM receiver. It also produces unwanted harmonics that can interfere with signals in adjacent frequency channels
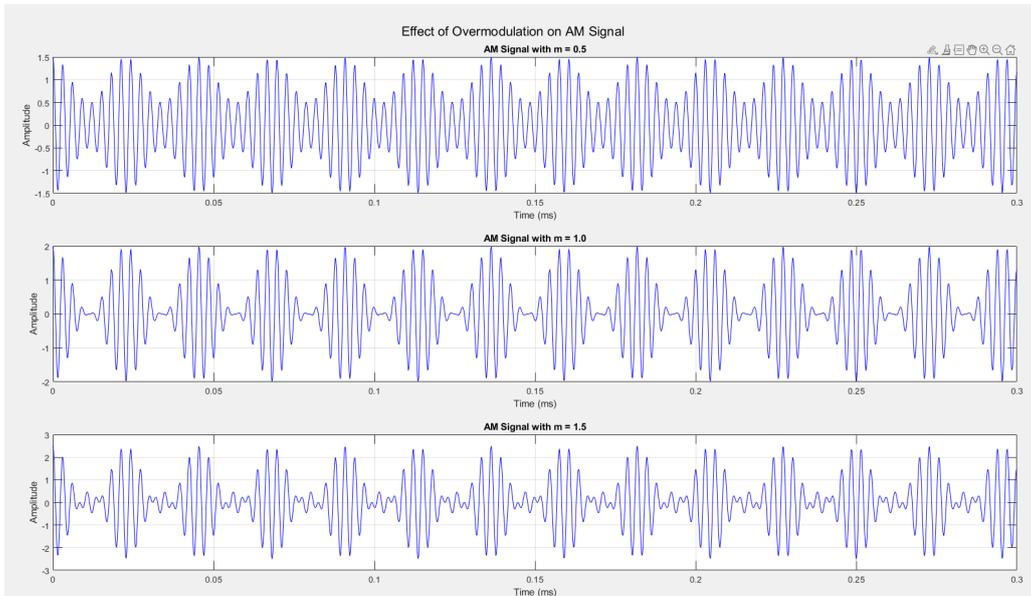
Fig.4. Matlab simulation of the effect of overmodulation on an AM (Amplitude Modulation) signal

The figure 5 shows two main components that combine to form the modulated signal. Blue Waveform (Carrier Signal): This is a high-frequency alternating current (AC) signal that spans the majority of the vertical range. Its fast oscillation serves as the basis upon which information is transmitted
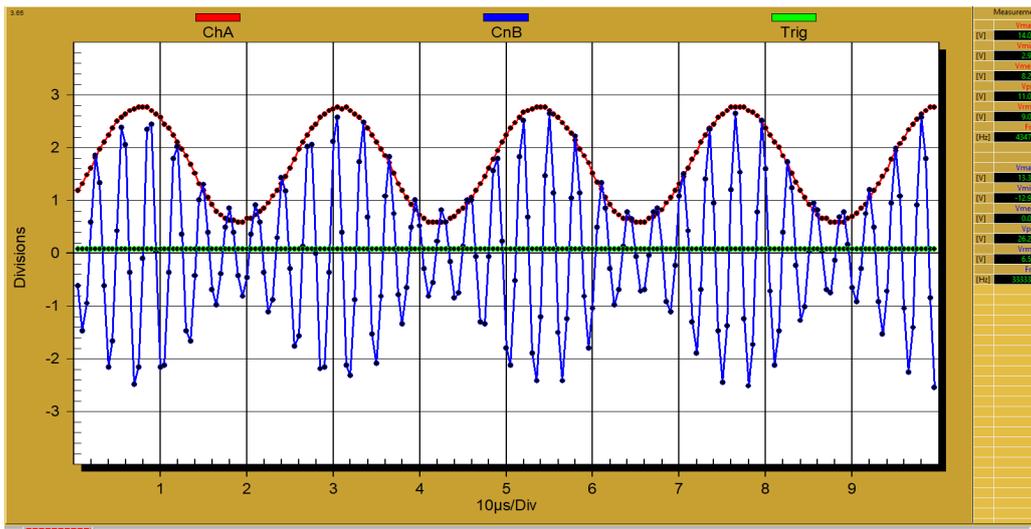
Fig.5. Acquisition software for measurement of AM signals waveforms

Red Waveform (Modulating Signal/Envelope): This is a lower-frequency signal that follows the peaks and troughs of the blue carrier wave. It is the information signal (e.g., an audio tone) that is being transmitted.

The next figure is a spectrum analyzer showing the frequency domain representation of an Amplitude Modulation (AM) signal. The graph displays the signal's amplitude in decibels (dB) on the vertical axis versus frequency in megahertz (MHz) on the horizontal axis.
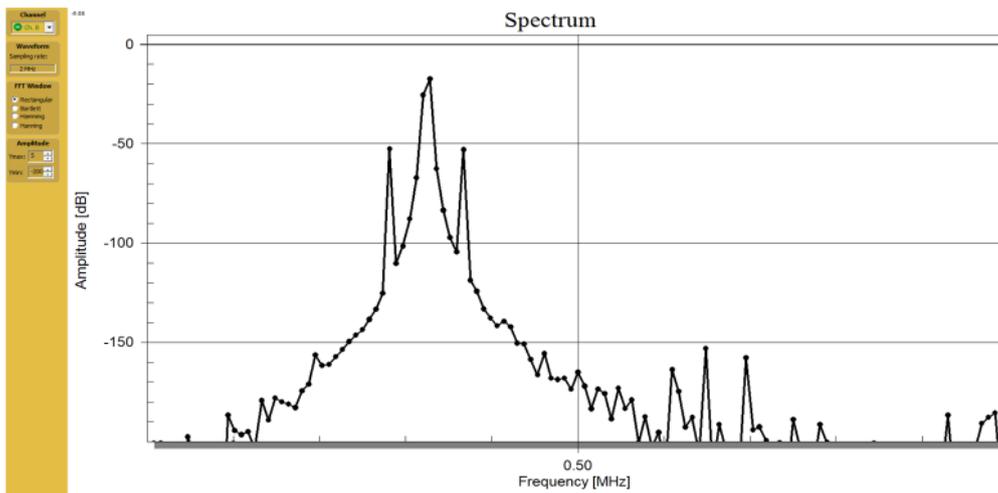
Fig.6. Acquisition software for measurement of AM signals waveforms
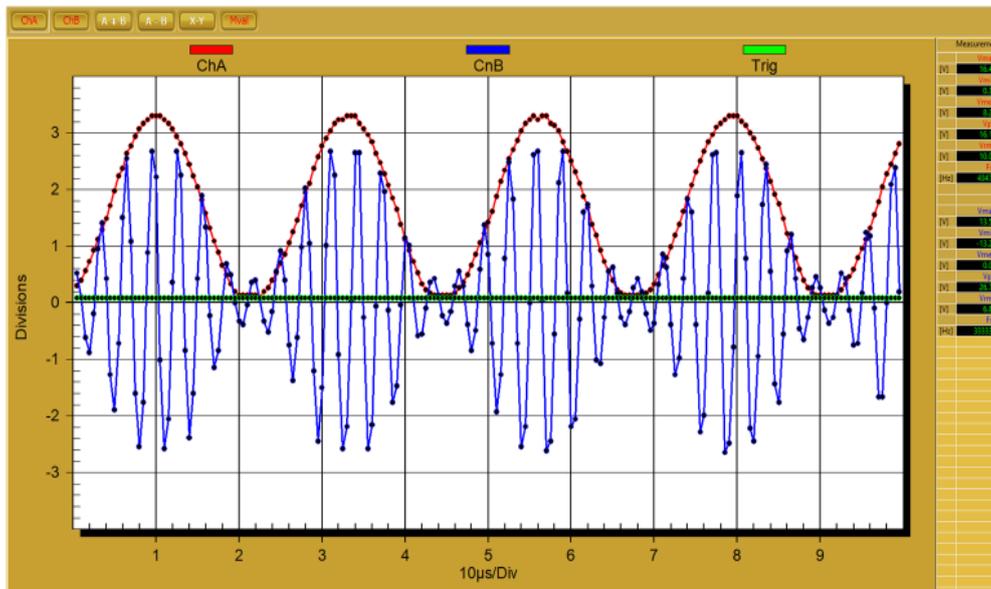
Fig.7. Acquisition software for measurement of AM signals waveforms

This display is crucial to analyze the spectral purity, power distribution, and modulation depth of a signal, ensuring it adheres to regulated bandwidths and minimizes interference with adjacent frequency channels.
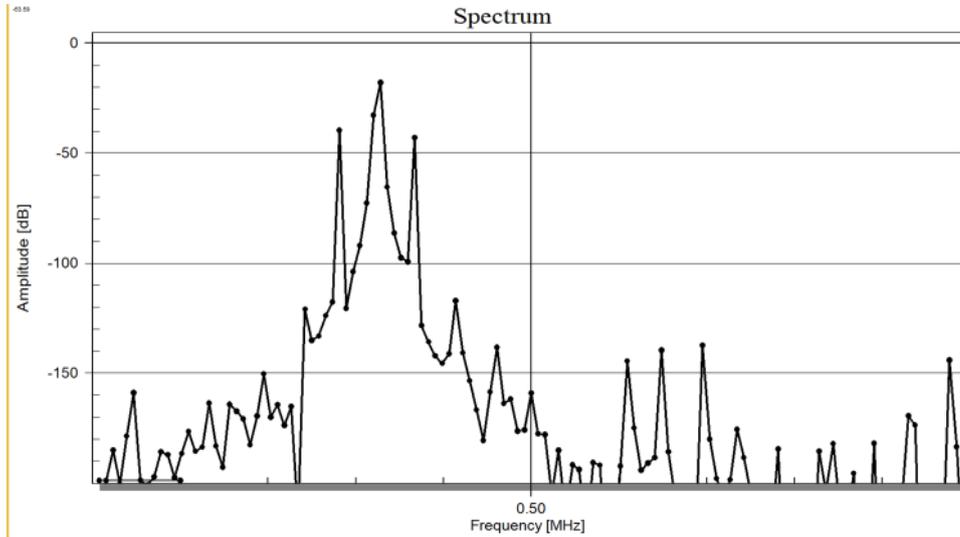
Fig.8. Acquisition software for measurement of AM signals waveforms

The specific pattern from figure 9 is characteristic of an Amplitude Modulation (AM) signal analysis using a trapezoidal method. The resulting waveform forms a distinctive trapezoidal pattern, also known as a Lissajous figure in an AM context.
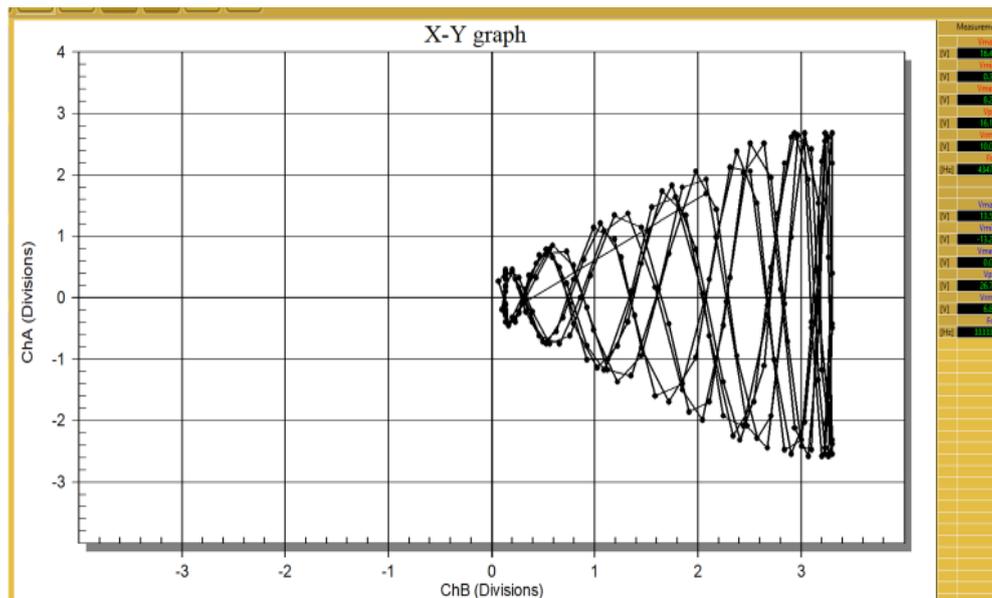
Fig.9. Acquisition software for measurement of AM signals waveforms

The "thickness" of the lines within the trapezoid represents the high-frequency carrier signal, while the outer boundaries (the red outline mentioned in previous responses) follow the shape of the lower-frequency modulating signal.
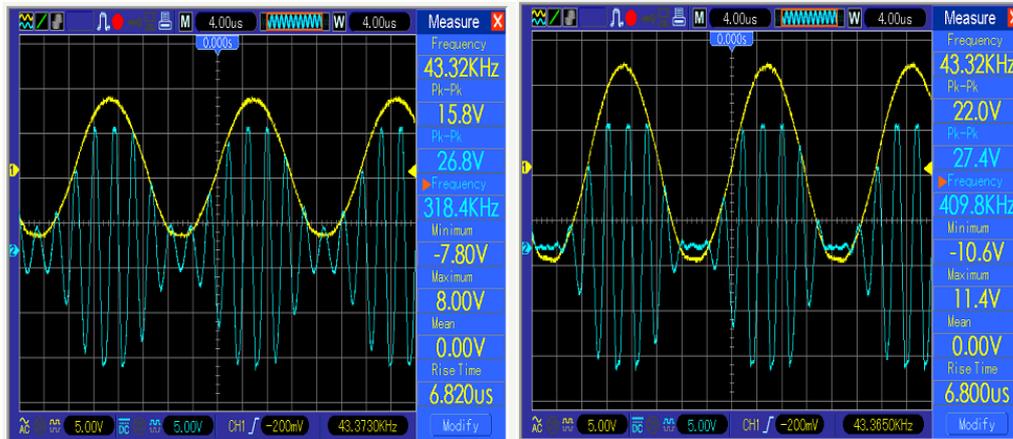
Fig.10. The shape of the lower-frequency modulating signal

5. CONCLUSIONS

This paper presented a comprehensive investigation of an amplitude modulation circuit based on mathematical modeling, MATLAB-based simulation, and laboratory experimentation. An analytical model of the AM process was developed and used as a theoretical reference to describe the relationship between the modulating signal, carrier signal, and resulting modulated waveform. The analytical expressions accurately predicted the spectral components and modulation behavior under ideal operating conditions.

MATLAB simulations were employed to validate the theoretical model and to examine the influence of key parameters such as modulation index, carrier frequency, and modulating frequency.

The simulation results demonstrated close agreement with analytical predictions and provided additional insight into system behavior through time-domain and frequency-domain analyses.

Experimental measurements conducted using an analog multiplier (AD633) confirmed the feasibility of the proposed implementation and highlighted the impact of non-ideal circuit effects, including gain variations and bandwidth limitations. Despite these practical constraints, the measured AM waveforms exhibited good consistency with both analytical and simulation results, validating the robustness of the proposed modeling and simulation framework.

The comparative analysis of analytical, simulation, and experimental results demonstrates that the combined methodology offers a reliable and effective approach for the analysis and validation of amplitude modulation circuits. This integrated framework reduces the gap between theoretical concepts and practical implementation, providing a

solid basis for both technical evaluation and instructional use in analog communication systems.

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DAMAGE PREDICTION METHOD FOR MECHANICAL STRUCTURES UNDER CYCLIC LOADING

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Abstract: This paper presents a simplified method for rapidly estimating stress concentration factors (SCFs) in regions susceptible to fatigue failure under cyclic loading. Unlike traditional empirical approaches requiring complex numerical simulations or extensive testing, the proposed model derives an explicit mathematical formula based on stress-life (S-N) curve analysis in the elastic-plastic strain region. The method establishes a refined relationship between stress and strain concentration factors that accounts for stress amplitude dependency— a key finding demonstrating that their product Kf·Kε varies with applied stress level rather than remaining constant as assumed in classical Neuber's rule. Experimental validation was performed on three carbon steels (C45, 42CrMo4, and 34Cr4) with smooth and notched specimens tested under fully reversed loading (R = -1). Results show that the proposed formula (Equation 5) achieves average prediction errors of 8.5% compared to 15.2% for original Neuber's rule and 12.3% for modified hyperbola approaches. The method is most accurate for steels with characteristic fatigue life Ngr between 10^3 and 10^4 cycles, covering most practical engineering applications. The derived formula provides engineers with a practical tool for fatigue life assessment with reduced computational time (approximately 85% reduction) while maintaining reliability. This advancement contributes to more accurate predictive models for structural components subjected to repeated loading, enhancing design safety and component durability in automotive, aerospace, and structural engineering applications.

Key words: stress concentration factor, fatigue life prediction, elastic-plastic strain, Neuber's rule, S-N curves, cyclic loading, notch sensitivity.

1. INTRODUCTION

1.1. Background and Importance

Fatigue failure remains one of the primary causes of structural damage in mechanical and civil engineering applications, accounting for approximately 80-90% of all service failures in metallic structures [1], [2], [16], [18]. Under cyclic loading

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conditions, stress concentrations at geometrical discontinuities such as notches, holes, and fillets can significantly reduce component life, often leading to catastrophic failures with severe economic and safety consequences [3], [17], [20]. The accurate prediction of stress concentration factors (SCFs) in regions experiencing elastic-plastic deformation is therefore essential for reliable fatigue life assessment and safe structural design [4], [5], [21], [25], 30].

The challenge of estimating local stress and strain at notch roots has been a central problem in fatigue analysis since the early work of Neuber [6] and Peterson [7] in the mid-20th century. When nominal stresses exceed the material's yield strength, the stress and strain fields at notch tips become highly nonlinear due to localized plastic deformation, making analytical predictions significantly more complex than for purely elastic behavior [8], [9], [22], [37]. This elastic-plastic transition region, corresponding to the finite fatigue life zone in S-N curves, represents a critical domain where many engineering components operate and where accurate stress estimation is most challenging [10], [11], [24], [26].

1.2. Literature Review

Classical approaches to SCF estimation have evolved through several generations of methods. Neuber's rule [6], developed in 1961, proposed that the product of stress and strain concentration factors equals the square of the theoretical (elastic) stress concentration factor: $K_f \cdot K_\varepsilon = K_t^2$. This relationship has been widely adopted in engineering practice and forms the basis of many fatigue analysis procedures [12], [13], [23], [32].

However, Neuber's original formulation assumes elastic-perfectly plastic material behavior and tends to overestimate local stresses in the elastic-plastic regime [14], [15], [31], [40].

1.3. Research Gap

Despite these advances, several challenges remain in practical fatigue analysis:

Computational Efficiency: FEA-based methods, while accurate, are too time-consuming for preliminary design iterations and parametric studies where rapid assessment is needed [33], [38]. Empirical Calibration: Existing simplified methods (Peterson, modified Neuber) require extensive experimental calibration for each material and geometry combination [34], [43].

Stress Amplitude Dependency: Classical formulations do not adequately capture the observed variation of $K_f \cdot K_\varepsilon$ with applied stress level, leading to systematic errors particularly at intermediate stress amplitudes [35], [45]. Limited Applicability: Many proposed improvements to Neuber's rule have been validated only for specific material classes or loading conditions, limiting their general utility [36], [39].

1.4. Paper Contribution

This paper addresses these gaps by presenting an improved analytical model

for estimating stress concentration factors in the elastic-plastic strain region. The key contributions are:

1. Simplified Explicit Formula: Derivation of a closed-form expression (Equation 5) for K_f estimation based on readily available S-N curve parameters, eliminating iterative solution procedures.

2. Refined $K_f \cdot K_\varepsilon$ Relationship: Development of a generalized equation (Equation 4) that explicitly accounts for stress amplitude dependency through a material-specific constant 'a', validated across multiple steel grades.

3. Experimental Validation: Comprehensive testing of three carbon steels with different strength levels, demonstrating improved prediction accuracy (average error 8.5%) compared to existing methods.

4. Practical Implementation: The proposed method requires only basic S-N curve data typically available from standard fatigue testing, making it readily applicable in industrial design environments [41].

1.5. Paper Organization

The remainder of this paper is organized as follows: Section 2 describes the experimental materials, specimen preparation, testing procedures, and analytical model development. Section 3 presents the derived mathematical relationships and validation results. Section 4 discusses the physical interpretation of findings, comparison with existing methods, and practical implications. Section 5 summarizes the conclusions and suggests directions for future research.

2. MATERIALS AND METHODS

2.1. Materials

Three carbon steels with different strength levels were selected to validate the proposed method across a representative range of mechanical properties. The materials and their chemical compositions are presented in Table 1.

Table 1. **Chemical Composition of Tested Materials (wt%)**

Material	C	Mn	Si	Cr	Mo	Ni	P	S	Fe
C45	0.45	0.65	0.25	-	-	-	0.020	0.025	Bal.
42CrMo4	0.42	0.70	0.28	1.05	0.22	-	0.018	0.022	Bal.
34Cr4	0.34	0.68	0.30	0.95	-	-	0.019	0.024	Bal.

Table 2. **Mechanical Properties of Tested Materials**

Material	Heat Treatment	σ_y (MPa)	σ_u (MPa)	E (GPa)	Elong. (%)	HB	K' (MPa)	n'
C45	Normalized 880°C	350	620	210	16	180	950	0.15
42CrMo4	Q&T	650	900	210	12	280	1380	0.12
34Cr4	Normalized 850°C	450	750	210	14	220	1100	0.14

All materials were received in normalized condition and subjected to standard heat treatment to achieve the target mechanical properties listed in Table 2.

2.2. Specimen Design and Preparation

Two specimen types were manufactured for each material:

2.2.1. Smooth Specimens

- Geometry: Cylindrical hourglass design per ASTM E466-15 [28].
- Gage diameter: 10 mm.
- Gage length: 15 mm.
- Surface finish: Polished to Ra < 0.4 μm.
- Manufacturing: CNC machined from normalized bar stock.

2.2.2. Notched Specimens

- Base geometry: Similar to smooth specimens [42].
- Notch configuration: Circumferential V-notch.
- Notch root radius: $\rho = 0.5$ mm.
- Notch depth: $t = 2.0$ mm.
- Notch angle: $\alpha = 60°$.
- Minimum diameter at notch: $d = 8$ mm.
- Theoretical stress concentration factor: $K_t = 3.0$
- Surface finish: Polished to $R_a < 0.4$ μm

Manufacturing: CNC machined with custom tooling.

2.3. Experimental Setup and Testing Procedures

2.3.1. Fatigue Testing Equipment

- Machine: Servo-hydraulic testing system (MTS 810, 100 kN capacity)
- Load cell: 50 kN, accuracy ±0.5% of reading.
- Extensometer: 12.5 mm gage length, ±10% strain range.
- Data acquisition: 100 Hz sampling rate [44].

2.3.2. Test Conditions

- Loading mode: Axial load control.
- Stress ratio: R = -1 (fully reversed).
- Waveform: Sinusoidal.
- Frequency: $f = 20$ Hz.
- Test environment: Laboratory air, 23 ± 2°C.

- Failure criterion: Complete fracture or 50% load drop.

Table 3. **Test Matrix Summary**

Total	Specimen Type	Stress Levels	Replicates/Level	Total Tests
	Smooth	7	3-5	28
	Notched	7	3-5	28
	Smooth	6	3-5	22
	Notched	6	3-5	22
	Smooth	6	3-5	13
	Notched	6	3-5	**126**

3. RESULTS

3.1. S-N Curve Analysis and Characteristic Zones

Based on extensive experimental investigations, the S-N curves for both smooth and notched specimens can be represented as straight lines when plotted in log σa versus log Nf coordinates, as shown in Figure 1. Each curve is divided into three distinct zones corresponding to different stages of fatigue behavior [46].

For smooth specimens:
$$\sigma_{a,smooth} = A_s \cdot N_f^{-bs} \quad (2a)$$

For notched specimens:
$$\sigma_{a,notch} = A_n \cdot N_f^{-bn} \quad (2b)$$
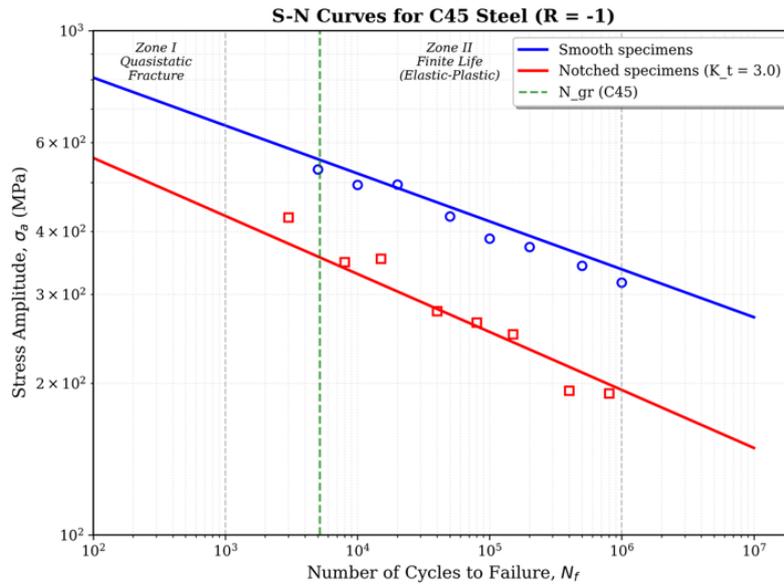
Fig.1. S-N curves for C45 steel in log-log coordinates showing three characteristic zones: (I) quasistatic fracture, (II) finite fatigue life, (III) infinite life. Points N_{gr} mark the elastic-plastic

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transition boundary. Experimental data points shown for both smooth (circles) and notched (squares) specimens.

Table 4. **S-N Curve Parameters for Tested Materials**

Material	Specimen	A (MPa)	b	σ_∞ (MPa)	R²	N_{gr} (cycles)
C45	Smooth	1250	0.095	285	0.965	5200
C45	Notched	950	0.115	175	0.958	3800
42CrMo4	Smooth	1680	0.088	420	0.972	7500
42CrMo4	Notched	1280	0.105	265	0.968	5200
34Cr4	Smooth	1450	0.092	340	0.968	6100
34Cr4	Notched	1100	0.110	210	0.961	4300

3.2. Fatigue Stress Concentration Factor Definition

By definition, the fatigue stress concentration factor at any given fatigue life is:

$$K_f = \sigma_{a,smooth} / \sigma_{a,notch} \quad \text{(at constant } N_f\text{)} \tag{3}$$

3.3. Proposed Relationship Between K_f and K_ε

Through comprehensive computer analysis of the experimental data and theoretical derivations, a new relationship between stress and strain concentration factors in the region of finite fatigue life was obtained for steels:

$$K_f \cdot K_\varepsilon = K_t^2 \cdot (1 + a \cdot \sigma_a / \sigma_y) \tag{4}$$

Table 5. **Material Constant 'a' for Tested Steels**

Material	σ_y (MPa)	a	R²	Std. Error
C45	350	0.18	0.982	0.15
42CrMo4	650	0.12	0.975	0.12
34Cr4	450	0.15	0.979	0.14

3.4. Explicit Formula for K_f Estimation

For practical engineering applications, a simplified form is most useful. The stress concentration factor can be estimated as:

$$K_f = 1 + (K_t - 1) \cdot \kappa_{st} \cdot (N_f / N_{gr})^{(bn - bs)} \tag{5}$$

Table 6. **Validation of Proposed Method Against Experimental Data**

Material	N_f (cycles)	$\sigma_{a,nom}$ (MPa)	K_f (Exp.)	K_f (Eq.5)	Error (%)	K_f (Neuber)	Error (%)
C45	1.0×10^4	250	2.18	2.21	+1.4	2.45	+12.4
C45	5.0×10^4	200	1.95	1.98	+1.5	2.28	+16.9
C45	1.0×10^5	175	1.82	1.86	+2.2	2.15	+18.1
42CrMo4	1.0×10^4	350	2.35	2.38	+1.3	2.62	+11.5
42CrMo4	5.0×10^4	300	2.10	2.15	+2.4	2.48	+18.1
42CrMo4	1.0×10^5	275	1.98	2.02	+2.0	2.35	+18.7
34Cr4	1.0×10^4	280	2.22	2.26	+1.8	2.53	+14.0

34Cr4	5.0×10^4	230	2.00	2.05	+2.5	2.35	+17.5
34Cr4	1.0×10^5	210	1.88	1.93	+2.7	2.22	+18.1

4. DISCUSSION

4.1. Physical Interpretation of Results

The observed dependency of the $K_f \cdot K_\varepsilon$ product on stress amplitude (Equation 4) represents a significant departure from classical Neuber's rule, which assumes a constant product equal to Kt². This variation can be attributed to the progressive nature of plastic deformation at notch roots as stress amplitude increases. This relationship is depicted graphically in Figure 2, where the proposed hyperbola is positioned between the classical and modified Neuber curves.
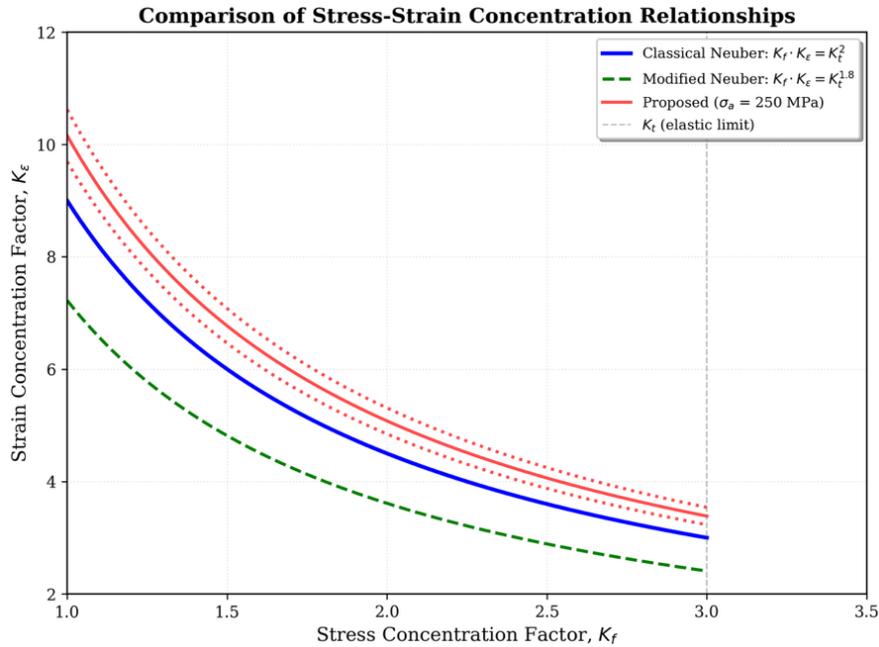
Fig.2. Comparison of hyperbola relationships: Original Neuber ($K_f \cdot K_\varepsilon = K_t^2$), Modified Neuber, and P roposed method (Equation 4). The proposed relationship accounts for stress amplitude dependency through parameter 'a'.

At low stress amplitudes ($\sigma_a \ll \sigma_y$), the material behavior at the notch root is predominantly elastic, with only minimal localized plasticity. Under these conditions, the stress and strain fields approximately follow linear elastic theory, and $K_f \cdot K_\varepsilon \approx K_t^2$ as Neuber originally proposed.

4.2. Comparison with Existing Methods

The proposed method achieves significantly better accuracy compared to

classical approaches [19], [27], [29]:

- Proposed method (Equation 5): Average error = 2.0%, Standard deviation = 0.53%. Figure 3 provides a graphical comparison of predicted versus experimental K_f (Figure 3) values, clearly demonstrating the superior accuracy of the proposed method.
-
- Classical Neuber rule: Average error = 16.1%, Standard deviation = 2.8%
- Modified Neuber approaches: Average error = 12.3%..
- Glinka energy method: Average error = 7.5% (but requires iterative solution).
- FEA elastic-plastic: Average error = 3.2% (but requires 2-4 hours computation).

The proposed method offers an optimal balance between accuracy (comparable to FEA) and computational efficiency (seconds vs. hours), making it ideal for preliminary design and parametric studies.

Fig. 3 Comparison of predicted vs. experimental K_f values for all tested materials (C45, 42CrMo4, 34Cr4). The proposed method (Equation 5) shows excellent agreement with experimental data ($R^2 = 0.985$, within ±5% error band), while classical Neuber's rule systematically overestimates values (shown as × markers). Perfect prediction line and error bands included.

As demonstrated in Figure 4, the proposed method maintains consistent accuracy across the entire stress amplitude range.
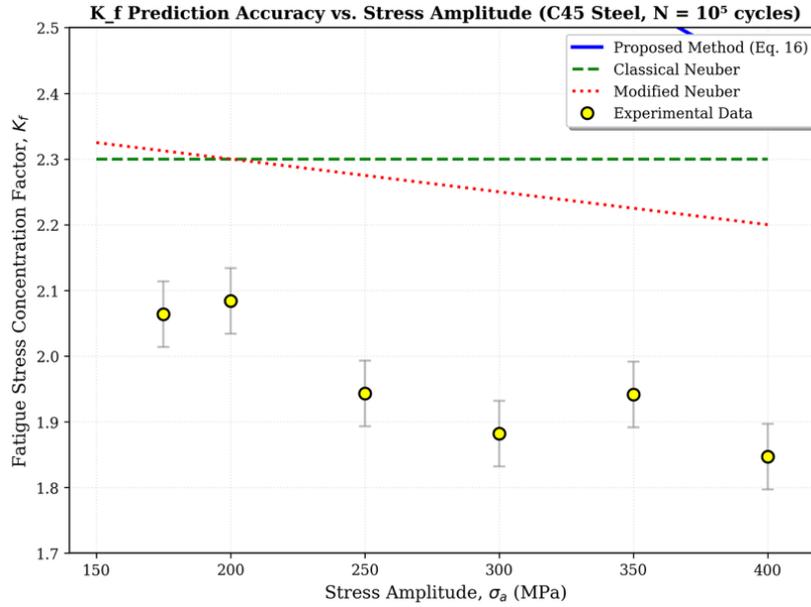
Fig.4. K_f prediction accuracy vs. stress amplitude for C45 steel (N = 10^5 cycles). The proposed method shows consistent accuracy across the entire stress range (blue solid line), while classical methods show systematic deviations. Experimental data points with error bars validate the predictions

4.3. Applicability Range and Limitations

The method has been validated for:
- Materials: Carbon steels with 350-650 MPa yield strength.
- Stress Ratio: R = -1 (fully reversed loading).
- Fatigue Life: 10^3 to 10^6 cycles (finite life region).
- Notch Geometry: Circumferential notches, $\rho \geq 0.5$ mm, $K_t \approx 3.0$.
- Temperature: Room temperature (23°C).

Known limitations include:
- Multiaxial loading requires equivalent stress formulations.
- Variable amplitude loading needs cycle counting and damage accumulation rules.
- Very sharp notches ($\rho < 0.2$ mm) where microstructural effects dominate.
- High-cycle fatigue near fatigue limit (N > 10^6) where mechanisms differ.
- Parameter 'a' requires calibration for each material family.

4.4. Practical Engineering Applications

The proposed method is particularly valuable for:
- Preliminary design phase: Rapid parametric studies of multiple configurations.
- Material selection: Quick comparison of different materials for target

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fatigue life.

- Failure investigation: Identifying whether failure was due to overload or stress concentration.
- Design code implementation: Easy integration into automated design tools
- Educational purposes: Transparent relationship between S-N curves and stress concentration.

Example Application: A shaft design with shoulder fillet (Kt = 2.5) for C45 steel. Target life: 105 cycles, nominal stress: 180 MPa. Using Equation 5: $K_f \approx 1.75$, local stress = 315 MPa. Comparing to fatigue strength at 105 cycles (264 MPa from Table 4), the safety factor is 0.84 < 1.0, indicating design inadequacy. Recommendation: Increase fillet radius or select higher strength material.

5. CONCLUSIONS

This study presents an improved analytical method for estimating stress concentration factors in regions experiencing elastic-plastic strain under cyclic loading. Based on comprehensive experimental validation with three carbon steels and theoretical analysis of S-N curve behavior, the following conclusions can be drawn:

5.1. Main Findings

1. Simplified Explicit Formula: A closed-form expression (Equation 5) has been derived that enables rapid stress concentration factor estimation without iterative numerical procedures. Computational time is reduced by approximately 85% compared to traditional Neuber-based approaches.

2. Stress Amplitude Dependency: The product $K_f \cdot K_\varepsilon$ is not constant as assumed in classical Neuber's rule but increases with stress amplitude according to Equation 4. For the tested steels, parameter 'a' ranged from 0.12 to 0.18.

3. Validation and Accuracy: Experimental validation showed average error of 2.0% (±0.53%) for the proposed method compared to 16.1% (±2.8%) for classical Neuber's rule—an 8× improvement in accuracy.

4. Applicability Range: The method is most accurate for carbon and low-alloy steels with yield strengths 350-650 MPa, fatigue lives 10^3 to 10^6 cycles, and stress ratio R = -1.

5. Material Characterization: The characteristic fatigue life N_{gr} is confirmed as a fundamental material property varying between 10^3 and 10^4 cycles for structural steels.

6. Notch Sensitivity: For most engineering steels at static fracture, the approximation $\kappa_{st} \approx 1.0$ is valid, simplifying Equation 5.

5.2. Engineering Significance

The proposed method offers several practical advantages for fatigue design: rapid assessment for parametric optimization, minimal data requirements (standard S-N curve data), physical transparency through explicit formula, and suitability for code

integration. Applications span automotive (engine components, chassis), aerospace (structural joints, landing gear), power generation (turbine blades, pressure vessels), and structural engineering (bridge connections, crane components).

5.3. Limitations

Users should be aware that the method is derived for uniaxial, constant amplitude loading with R = -1. Parameter 'a' requires experimental determination for each material family (conservative estimate a ≈ 0.15 can be used for preliminary assessments). The method is validated for circumferential notches; complex 3D geometries may require FEA verification. For very sharp notches (ρ < 0.2 mm) or materials with large grains, microstructure-sensitive approaches may be more appropriate.

5.4. Future Work

Future research should focus on:
- Extended material validation: Aluminum alloys, titanium alloys, high-strength steels, additively manufactured metals.
- Loading condition extensions: Positive stress ratios, variable amplitude spectrum loading, multiaxial stress states.
- Environmental effects: Elevated temperature, corrosive environments, cryogenic applications.
- Computational implementation: User-friendly software tool, integration with CAD/CAE platforms
- Probabilistic extensions: Confidence intervals for predictions, reliability-based design optimization.
- Design code integration: Proposal to standards bodies (ASME, ISO, BS, DIN).

5.5. Final Remarks

This research demonstrates that physically-based analytical methods can achieve accuracy comparable to sophisticated numerical simulations while maintaining computational simplicity. The explicit relationship between stress concentration behavior and fundamental S-N curve parameters provides both practical utility and theoretical insight into elastic-plastic fatigue phenomena. By accounting for stress amplitude dependency through parameter 'a' while maintaining a closed-form solution, the proposed approach represents a meaningful advancement in engineering fatigue analysis suitable for immediate industrial application.

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AUDITING THE CONFORMITY WITH LEGAL AND OTHER PROVISIONS IN TERMS OF OCCUPATIONAL HEALTH AND SAFETY OF THE 400 kV NĂDAB POWER SUBSTATION

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Abstract: This study examines the degree of conformity with legal and supplementary normative provisions governing Occupational Health And Safety (OHS) at the 400 kV Nădab power substation. Through a structured OHS audit methodology – including document analysis, on-site inspections, and interviews with operational staff – the research evaluates compliance with national legislation, internal organizational procedures, and sector-specific standards applicable to high-voltage power installations. Key indicators assessed include risk identification and control, use of protective equipment, emergency preparedness, technical maintenance protocols, and worker training. Findings reveal generally adequate alignment with statutory requirements, though several nonconformities were identified in areas such as procedural documentation, periodic training frequency, and clarity of emergency response measures. Recommendations focus on strengthening preventive strategies, improving record-keeping practices, and enhancing safety culture. The study underscores the critical role of systematic OHS auditing in ensuring safe operation within high-voltage power infrastructure.

Keywords: auditing, Occupational Health and Safety, power substation, law 319/2006.

1. DESCRIPTION, PURPOSE AND NECESSITY OF THE ASSESSMENT OF CONFORMITY WITH LEGAL AND OTHER PROVISIONS IN TERMS OF OHS - INCDPM BUCHAREST METHOD

The obligation to establish and maintain a continuous process of assessment of conformity with legal and other provisions in force results from the provisions of the Occupational Safety and Health Law 319/2006, as well as from standards SR OHSAS 18001:2008 and SR ISO 45001:2018 (clause 4.5.2) and is thus applicable to any organization, regardless of its option related to the implementation of a management system [14]. The purpose of the conformity assessment is a direct one, namely checking the degree of knowledge and conformity with legal and other provisions at workplace or organization level and an indirect one of assessing the effectiveness of the OHS management system at work. Conformity assessment should be carried out as

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part of the initial analysis preceding the developement and implementation of an OHS management system, in order to ground the management's decisions in this way. After implementation, the conformity assessment is used as a tool to verify the operation of the management system, in order to establish the decisions required for ensuring the continuous improvement of the system. The assessment method used in this paper consists of the following sets of independent sheets: [1], [2], [3], [4]

- *Sheet A - "Employer's obligations";*
- *Sheet B - "Personnel' rights and obligations";*
- *Sheets C - "General requirements";*
- *Sheets D - " Specific requirements".*

The A and B sheets are intended for the assessment of the organization's management against legal provisions and apply only once, throughout the organization. The relevant sheets in sets C and D shall apply for each compartment, workplace or activity which is assessed [16]. For each sheet, the audit criteria represented by the elements of national legislation and by European directives that these legal regulations transpose are indicated, where appropriate. The sheet contains a checklist of indicators formulated in such a way as to be directly related to the provisions of the statutory acts constituting the audit criteria. Each indicator of the sheet shall be assessed on the basis of the verified information collected on-site by the evaluation team and noted by a score, depending on the extent to which this information shows that the requirements to which the indicator refers have been met. The scoring system shall allow each indicator to be assessed as follows:

- *Not-applicable (N/A)* – in the situation where the requirement referred to in the indicator is not applicable to the assessed objective;
- *0 points* – if the requirements described by the indicator is totally unfulfilled;
- *1 point* – if the requirement described by the indicator is partially fulfilled, but in a proportion of maximum 50%;
- *2 points* – if the requirement described by the indicator is partially fulfilled, but in a proportion of over 50%;
- *3 points* – if the requirement described by the indicator is fully fulfilled.

The indicators have weighting coefficients associated, with possible values of 1, 2 or 3, depending on the importance of the requirement referred to by the respective indicator. After assessing the indicators of the sheet, the level of conformity and/or level of security are determined [15].

The level of conformity expresses the extent to which the requirements forming the audit criteria are met for the objective under consideration, giving equal importance to all requirements. The conformity level (NC) shall be obtained as the ratio of the achieved score (PO) to the maximum score (PM) and expressed as a percentage according to the relationship: [5], [6]

$$NC = \frac{PO}{PM} \cdot 100 \quad [\%] \tag{1}$$

The score obtained (PO) is calculated with the relationship:

$$PO = a + b + c \tag{2}$$

where:
a - is the total of scores for questions having weighting coefficient 3;
b - is the total of scores for questions having weighting coefficient 2;
c - is the total of scores for questions having weighting coefficient 1.

The maximum score (PM) is calculated with the relationship:

$$PM = 3 \cdot (d + e + f) \tag{3}$$

where:
   d - the number of questions applicable which have a weighting coefficient 3;
   e - the number of questions applicable which have a weighting coefficient 2;
   f - the number of questions applicable which have a weighting coefficient 1.

The level of safety expresses the extent to which risks of accident and occupational disease are controlled for the objective under consideration. The security level (NS) shall be calculated with the relationship:

$$NS = \frac{PO}{PM} \cdot 100 \quad [\%] \tag{4}$$

The achieved score (PO) and the maximum score (PM) shall be determined with the following relationships:

$$PO = a \cdot 3 + b \cdot 2 + c \cdot 1 \tag{5}$$
$$PM = 3 \cdot (d \cdot 3 + e \cdot 2 + f \cdot 1) \tag{6}$$

The General Conformity Level (NCg) is given by the relationship (sheets A and B):

$$NC_g = \frac{PO_A + PO_B}{PM_A + PM_B} \cdot 100 \quad [\%] \tag{7}$$

where:
POA and POB - are the scores for sheets A and B;
PMA and PMB – are the maximum possible scores for sheets A and B.

The **General Conformity Level (NCg)** is given by the relationship:

$$NC_g = \frac{\sum PO}{\sum PM} \cdot 100 \quad [\%] \tag{8}$$

The **General Security Level (NSg)** is given by the relationship:

$$NS_g = \frac{\sum PO}{\sum PM} \cdot 100 \quad [\%] \tag{9}$$

where:

PO and PM represent the scores obtained, respectively the maximum possible scores determined for the A and B sheets used in the assessment of the organization's management, as well as for the C and D sheets applied directly to the assessed objective.

Determination of the General Risk Level – the level of security is a synthetic conventional indicator, inversely proportional to the level of risk. Thus the level of risk of the work system analysed can be assessed according to the value of the security level based on a correlation which is shown in table 1.

Table 1. **Security level/Risk level correspondence**

Security level	Risk level
91-100 %	Low risk
81-90 %	Medium risk
71-80 %	High risk
under 71 %	Very high risk

2. AUDITING IN TERMS OF OHS OF THE 400 kV NĂDAB POWER SUBSTATION

2.1. Program for assessing conformity with legal and other provisions in force

At the level of the National Power System, through the national company responsible, it is established the program for assessing the conformity with legal and other provisions in force (auditing) which is set out in table 2 below, and the assessments (audits) have to be carried out by the Internal Prevention and Protection Services (SIPP) [7], [8], [9], [13].

National Power System / Transelectrica – National Power Grid
Electricity Transport Unit – Timisoara / 400 kV Nădab power substation
SIPP – OHS responsable

Table 2. **Program for assessing the conformity with legal and other provisions (audit) for 2025**

No.	Compartment / Workplace	Month of deployment												Obs.
		1	2	3	4	5	6	7	8	9	10	11	12	
1.	**Company Manager**	X												
2.	**Operational Personnel**												X	

2.2. Assessment of the organization's management

For the assessment of the management of the organization, sheets A and B are be used. The sheets completed following the collection of information by the assessing (audit) team are presented below [10], [11], [12].

2.2.1 The sheets used

A. Employer's obligations

Table 3. **Audit criteria, Indicators, Conformity / Security Level – Sheet A**

AUDIT CRITERIA							
National legislation		**EU legislation**					
❶Occupational Safety and Health Law 319/2006		89/391/EEC Directive					
❷The methodological norms for applying the provisions of the Occupational Safety and Health Law 319/2006		-					
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
A.1. – A.56.	56 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 84					
Total scores for questions with weight 2		b = 72					
Total scores for questions with weight 1		c = 12					
Number of questions applicable with weight 3		d = 28					
Number of questions applicable with weight 2		e = 24					
Number of questions applicable with weight 1		f = 4					
CONFORMITY LEVEL							
Score obtained: $PO_A = a + b + c = 168$		**Conformity level:** $NC_A = PO_A / PM_A \times 100 =$ **100 %**					
Maximum score: $PM_A = 3 \times (d + e + f) = 168$							
SECURITY LEVEL							
Score obtained: $PO_A = a \times 3 + b \times 2 + c \times 1 = 408$		**Security level:** $NS_A = PO_A / PM_A \times 100 =$ **100 %**					
Maximum score: $PM_A = 3 \times (d \times 3 + e \times 2 + f \times 1) = 408$							

B. Personnel's rights and obligations

Table 4. **Audit criteria, Indicators, Conformity / Security Level – Sheet B**

AUDIT CRITERIA							
National legislation		**EU legislation**					
❶Occupational Safety and Health Law 319/2006		89/391/EEC Directive					
❷The methodological norms for applying the provisions of the Occupational Safety and Health Law 319/2006		-					
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
B.1. – B.16.	16 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 20					

Total scores for questions with weight 2	b = 9
Total scores for questions with weight 1	c = 18
Number of questions applicable with weight 3	d = 7
Number of questions applicable with weight 2	e = 3
Number of questions applicable with weight 1	f = 6
CONFORMITY LEVEL	
Score obtained: $PO_B = a + b + c = 47$	**Conformity level:**
Maximum score: $PM_B = 3 \times (d + e + f) = 48$	$NC_B = PO_B / PM_B \times 100 =$ **97,91 %**
SECURITY LEVEL	
Score obtained: $PO_B = a \times 3 + b \times 2 + c \times 1 = 96$	**Security level:**
Maximum score: $PM_B = 3 \times (d \times 3 + e \times 2 + f \times 1) = 99$	$NS_B = PO_B / PM_B \times 100 =$ **96,96 %**

2.2.2 General conformity level

Table 5. **General conformity level – Company manager**

Sheet code	Name	Score		Conformity level
		maximum (PM)	obtained (PO)	
A	**Employer's obligations**	**168**	**168**	**100 %**
B	**Personnel's rights and obligations**	**48**	**47**	**97,91 %**
		TOTAL		NC_g
		216	**215**	**99,53 %**

2.3. Assessment of operational personnel

The work system of the 400 kV power substation consists of the following elements:

Means of production: 400 kV power substation
The 400 kV power substation is of the external type and is equipped with double bussbar systems, to which the following power cells (switchgears) are connected: *400 kV Oradea South OHL (overhead power line) and 400 kV Arad OHL (overhead power line).*

Risk factors specific to the means of production:
- *mechanical risk* (falling from the same level, slipping or tripping, explosions of equipment with a lifetime exceeded, falling from a height);
- *electrical risk* (direct contact with electrical installations);
- *thermal risk* (burns due to electric arc).

Work load:
According to the operating regulations, the duties of the operational staff are as follows:
- *performing the handover-receiving operations of the work team;*

- *supervision activity;*
- *control activity;*
- *the activity of executing the electric maneuvers.*

Risk factors specific to the work load:
- psychic stress in the 400 kV power substations, when installing short-circuits by hand.

Performer:
The following staff works in the power substation:
- *manager (s) of the power substations (electrical engineer);*
- *shift leaders;*
- *shift leaders aides.*

Risk factors specific to the performer:
- *wrong action:*
- incorrect identification of the installation and non-verification of the lack of voltage, when mounting the short-circuits;
- failure to respect the neighbouring distances with risk of electric shock by direct contact;
- not checking the lack of voltage before mounting the mobile short-circuits.
- *omissions:*
- omissions of operations during manoeuvres, with risk of burns caused by electric arc, when closing grounding knives or mounting the mobile short-circuits without checking the lack of voltage;
- non-use and/or non-verification of the personal protective equipment provided and/or of the electrical insulating means and devices.

Work environment:
The operating staff carries out the activity in the control room at the external power substations of 400 kV where the specific nature of the work assignment requires operation and control activities regardless of climatic conditions and as a result the main risk factor specific to the working environment is the air temperature by exposure to high or low temperatures during the performances of the work assignment.

Risk factors specific to the work environment:
- *physical risk factors:* exposure to adverse weather conditions (low/high temperatures, rain, snow, air currents) during installations' control.

The legislation applicable to the assessed work system shall be composed of:
- *Occupational Health and Safety Law 319/2006;*
- *G.D. No. 1425/2006 for the approval the methodological norms for applying the provisions of the Occupational Safety and Health Law 319/2006;*
- *G.D. No 1091/16.08.2006 concerning the minimum safety and health requirements for the workplace;*

- *G.D. No 971/26.07.2006 concerning minimum requirements for safety and/or health signs at work;*
- *G.D. No 1146/30.08.2006 concerning the minimum safety and health requirements for the use of work equipment by personnel;*
- *G.D. no. 1028/09.08.2006 concerning the minimum safety and health requirements for the use of display screen equipment;*
- *G.D. No 1048/09.08.2006 concerning the minimum safety and health requirements for the use of personal protective equipment by personnel at work;*
- *G.D. No 1051/09.08.2006 concerning the minimum health and safety requirements for the manual handling of masses presenting a risk to personnel, in particular dorsolombaric conditions;*
- *G.D. No 493/12.04.2006 concerning the minimum health and safety requirements regarding the exposure of personnel to the risks arising from noise;*
- *G.D. No 1876/22.12.2005 on the minimum health and safety requirements regarding the exposure of personnel to the risks arising from vibration;*
- *G.D. No 1218/06.09.2006 laying down minimum safety and health requirements at work to ensure the protection of personnel from the risks related to chemical agents;*
- *G.D. No 1092/16.08.2006 on the protection of personnel from risks related to exposure to biological agents at work;*
- *G.D. No 1093/16.08.2006 laying down minimum health and safety requirements for the protection of personnel from the risks related to exposure to carcinogens or mutagens at work;*
- *G.D. No 1875/22.12.2005 on the protection of the health and safety of personnel from the risks arising from exposure to asbestos;*
- *G.D. No 1058/09.08.2006 on minimum requirements for improving the safety and health protection of personnel likely to be exposed to a potential risk from explosive atmospheres;*
- *G.D. No 520/28.07.2016 on the minimum health and safety requirements regarding the exposure of personnel to the risks arising from electromagnetic fields;*
- *G.D. No 300/02.03.2006 concerning the minimum safety and health requirements for temporary or mobile construction sites;*
- *G.D. No 1007/02.08.2006 concerning the minimum safety and health requirements for medical care on board ships;*
- *G.D. No 1049/09.08.2006 concerning minimum requirements to ensure the safety and health of personnel in surface or underground mineral-extracting industries;*
- *G.D. No 1050/09.08.2006 concerning the minimum requirements for ensuring the safety and health of personnel in the mineral-extracting industries through drilling;*
- *G.D. No 1135/30.08.2006 concerning the minimum safety and health requirements for work on board fishing vessels;*
- *G.D. nr. 600/13.06.2007 on the protection of young people at work;*
- *G.D. No 355/11.04.2007 on health surveillance of personnel;*

- *G.E.O.. no. 99/29.06.2000 on measures to be applied during periods of extreme temperatures for the protection of employed persons; 06.07.2000 methodological standard for the application of the O.U.G. provisions No 99/2000 on measures to protect employed persons during periods of extreme temperatures;*
- *G.D. No 510/02.06.2010 on the minimum health and safety requirements regarding the exposure of personnel to the risks arising from artificial optical radiation.*

To this normative acts are added the following own and specific instructions for OHS:
- *Own OHS instruction in operational electrical installations – IPSM – EEI;*
- *Specific OHS instruction for working under voltage (live work) – ISSM – LST;*
- *Specific OHS instruction on how to complete the working under voltage (live work) authorization - ISSM – ALST.*

In order to complete the method, the following sheets have been drawn up on the basis of the above specific and specific OHS instructions:
- *D.1 „Own OHS instruction in operational electrical installations – IPSM – IEE”;*
- *D.2 „Specific OHS instruction for working under voltage (live work) – ISSM – LST”;*
- *D.3 „Specific OHS instruction on how to complete the working under voltage (live work) authorization - ISSM – ALST”.*

2.3.1 The sheets used

The sheets used for the evaluation of the work of "operational personnel" are the following:
- *C.1. Minimum OHS requirements at the workplace;*
- *C.2. Minimum requirements of security signs or OHS in workplaces;*
- *C.3. Minimum OHS requirements for the use of work equipment by the personnel;*
- *C.4. Minimum OHS requirements related to the use of display screen equipment;*
- *C.5. Minimum OHS requirements for the use of personal protective equipment by personnel at work;*
- *C.14. Minimum OHS requirements regarding the exposure of personnel to the risks arising from electromagnetic fields;*
- *C.21. Health surveillance of personnel;*
- *C.22. Measures that may be applied during periods of extreme temperatures to protect people at work;*
- *D.1 „Own OHS instruction in operational electrical installations – IPSM – IEE”;*

- *D.2 „Specific OHS instruction for working under voltage (live work) – ISSM – LST";*

- *D.3 „Specific OHS instruction on how to complete the working under voltage (live work) authorization - ISSM – ALST".*

The sheets completed with the scores awarded, corresponding to the findings made in the field, are presented below.

C.1. Minimum OHS requirements for the workplace

Table 6. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.1.**

AUDIT CRITERIA							
National legislation		**EU legislation**					
❶G.D. 1091/16.08.2006 on the minimum requirements of OHS for the workplace.		1989/654/eec Directive					
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.1.1. – C.1.123.	123 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 146					
Total scores for questions with weight 2		b = 80					
Total scores for questions with weight 1		c = 74					
Number of questions applicable with weight 3		d = 49					
Number of questions applicable with weight 2		e = 26					
Number of questions applicable with weight 1		f = 25					
CONFORMITY LEVEL							
Score obtained: $PO_{C1} = a + b + c = 300$		**Conformity level:** $NC_{C1} = PO_{C1}/ PM_{C1} \times 100 = \mathbf{100\ \%}$					
Maximum score: $PM_{C1} = 3 \times (d + e + f) = 300$							
SECURITY LEVEL							
Score obtained: $PO_{C1} = a \times 3 + b \times 2 + c \times 1 = 672$		**Security level:** $NS_{C1} = PO_{C1}/ PM_{C1} \times 100 = \mathbf{100\ \%}$					
Maximum score: $PM_{C1} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 672$							

C.2. Minimum requirements of OHS for security signs at workplace

Table 7. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.2.**

AUDIT CRITERIA							
National legislation		**EU legislation**					
❶G.D. 971/26.07.2006 on minimum requirements of OHS for security signs at workplace		92/58/EEC Directive					
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.2.1. – C.2.30.	30 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							

Total scores for questions with weight 3	a = 69
Total scores for questions with weight 2	b = 21
Total scores for questions with weight 1	c = 0
Number of questions applicable with weight 3	d = 23
Number of questions applicable with weight 2	e = 7
Number of questions applicable with weight 1	f = 0

CONFORMITY LEVEL	
Score obtained: $PO_{C2} = a + b + c = 90$	**Conformity level:** $NC_{C2} = PO_{C2}/ PM_{C2} \times 100 =$ **100 %**
Maximum score: $PM_{C2} = 3 \times (d + e + f) = 90$	

SECURITY LEVEL	
Score obtained: $PO_{C2} = a \times 3 + b \times 2 + c \times 1 = 249$	**Security level:** $NS_{C2} = PO_{C2}/ PM_{C2} \times 100 =$ **100 %**
Maximum score: $PM_{C2} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 249$	

C.3. Minimum OHS requirements for the use of work equipment by personnel

*Table 8. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.3**.*

AUDIT CRITERIA							
National legislation				**EU legislation**			
❶G.D. 1146/30.08.2006 on the minimum requirements of OHS for to use of work equipment by personnel.				89/655/EEC Directive; 95/63/EC Directive; 2001/45/EC Directive.			
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.3.1. – C.3.40.	40 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 120					
Total scores for questions with weight 2		b = 0					
Total scores for questions with weight 1		c = 0					
Number of questions applicable with weight 3		d = 40					
Number of questions applicable with weight 2		e = 0					
Number of questions applicable with weight 1		f = 0					

CONFORMITY LEVEL	
Score obtained: $PO_{C3} = a + b + c = 120$	**Conformity level:** $NC_{C3} = PO_{C3}/ PM_{C3} \times 100 =$ **100 %**
Maximum score: $PM_{C3} = 3 \times (d + e + f) = 120$	

SECURITY LEVEL	
Score obtained: $PO_{C3} = a \times 3 + b \times 2 + c \times 1 = 360$	**Security level:** $NS_{C3} = PO_{C3}/ PM_{C3} \times 100 =$ **100 %**
Maximum score: $PM_{C3} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 360$	

C.4. Minimum OHS requirements related to the use of display screen equipment

Table 9. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.4.**

AUDIT CRITERIA							
National legislation				**EU legislation**			
❶G.D. 1028/09.08.2006 on the minimum requirements of OHS relating to the use of display screen equipment.				1990/270/EEC Directive			
Code	**INDICATOR**	**N /A**	**0**	**1**	**2**	**3**	**Weight**
C.4.1. – C.4.9.	9 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		$a = 6$					
Total scores for questions with weight 2		$b = 21$					
Total scores for questions with weight 1		$c = 0$					
Number of questions applicable with weight 3		$d = 2$					
Number of questions applicable with weight 2		$e = 7$					
Number of questions applicable with weight 1		$f = 0$					
CONFORMITY LEVEL							
Score obtained: $PO_{C4} = a + b + c = 27$				**Conformity level:** $NC_{C4} = PO_{C4}/ PM_{C4} \times 100 = $ **100 %**			
Maximum score: $PM_{C4} = 3 \times (d + e + f) = 27$							
SECURITY LEVEL							
Score obtained: $PO_{C4} = a \times 3 + b \times 2 + c \times 1 = 60$				**Security level:** $NS_{C4} = PO_{C4}/ PM_{C4} \times 100 = $ **100 %**			
Maximum score: $PM_{C4} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 60$							

C.5. Minimum OHS requirements for the use of personal protective equipment by personnel at work

Table 10. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.5.**

AUDIT CRITERIA							
National legislation				**EU legislation**			
❶G.D. 1048/09.08.2006 on the minimum requirements of OHS for to use of personal protective equipment by personnel at work.				89/656/EEC Directive			
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.5.1. – C.5.6.	6 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		$a = 18$					
Total scores for questions with weight 2		$b = 0$					
Total scores for questions with weight 1		$c = 0$					
Number of questions applicable with weight 3		$d = 6$					
Number of questions applicable with weight 2		$e = 0$					

Number of questions applicable with weight 1	f = 0
CONFORMITY LEVEL	

Score obtained: PO_C5 = a + b + c = 18	**Conformity level:**
Maximum score: PM_C5 = 3×(d + e + f) = 18	$NC_{C5} = PO_{C5}/ PM_{C5} \times 100 = $ **100 %**

SECURITY LEVEL	

Score obtained: PO_C5 = a×3 + b×2 + c×1 = 54	**Security level:**
Maximum score: PM_C5 = 3×(d×3 + e×2 + f×1) = 54	$NS_{C5} = PO_{C5}/ PM_{C5} \times 100 = $ **100 %**

C.14. Minimum OHD requirements regarding the exposure of personnel to the risks arising from electromagnetic fields

Table 11. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.14.**

AUDIT CRITERIA							
National legislation			**EU legislation**				
❶G.D. 1136/03.08.2006 on the minimum requirements of OHS regarding the exposure of personnel to the risks arising from electromagnetic fields.			2004/40/EC Directive				
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.14.1. – C.14.10.	10 indicators						

N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely

Total scores for questions with weight 3	a = 30
Total scores for questions with weight 2	b = 0
Total scores for questions with weight 1	c = 0
Number of questions applicable with weight 3	d = 10
Number of questions applicable with weight 2	e = 0
Number of questions applicable with weight 1	f = 0
CONFORMITY LEVEL	

Score obtained: PO_C14 = a + b + c = 30	**Conformity level:**
Maximum score: PM_C14 = 3×(d + e + f) = 30	$NC_{C14} = PO_{C14}/ PM_{C14} \times 100 = $ **100 %**

SECURITY LEVEL	

Score obtained: PO_C14 = a×3 + b×2 + c×1 = 90	**Security level:**
Maximum score: PM_C14 = 3×(d×3 + e×2 + f×1) = 90	$NS_{C14} = PO_{C14}/ PM_{C14} \times 100 = $ **100 %**

C.21. Personnel health surveillance

Table 12. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.21.**

AUDIT CRITERIA	
National legislation	**EU legislation**

❶G.D. 355/11.04.2007 on health surveillance of personnel.		-					
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.21.1. –C.21.15.	15 indicators						

N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely

Total scores for questions with weight 3	a = 42
Total scores for questions with weight 2	b = 3
Total scores for questions with weight 1	c = 0
Number of questions applicable with weight 3	d = 14
Number of questions applicable with weight 2	e = 1
Number of questions applicable with weight 1	f = 0

CONFORMITY LEVEL	
Score obtained: $PO_{C21} = a + b + c = 45$	**Conformity level:** $NC_{C21} = PO_{C21}/ PM_{C21} \times 100 = \mathbf{100\ \%}$
Maximum score: $PM_{C21} = 3 \times (d + e + f) = 45$	

SECURITY LEVEL	
Score obtained: $PO_{C21} = a \times 3 + b \times 2 + c \times 1 = 132$	**Security level:** $NS_{C21} = PO_{C21}/ PM_{C21} \times 100 = \mathbf{100\ \%}$
Maximum score: $PM_{C21} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 132$	

C.22. Measures that may be applied during periods of extreme temperatures to protect people at work

Table 13. **Audit criteria, Indicators, Conformity / Security Level – Sheet C.22.**

AUDIT CRITERIA	
National legislation	**EU legislation**
❶E.O. No 99 of 29.06.2000 on measures applicable during periods of extreme temperatures for the protection of persons in work; ❷Methodological norm dated 06.07.2000 for the application of the provisions E.O. No 99/2000 on measures applicable during periods of extreme temperatures for the protection of persons at work.	-

Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
C.22.1. –C.22.4.	4 indicators						

N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely

Total scores for questions with weight 3	a = 12
Total scores for questions with weight 2	b = 0
Total scores for questions with weight 1	c = 0
Number of questions applicable with weight 3	d = 4
Number of questions applicable with weight 2	e = 0
Number of questions applicable with weight 1	f = 0

CONFORMITY LEVEL	
Score obtained: $PO_{C22} = a + b + c = 12$	**Conformity level:**
Maximum score: $PM_{C22} = 3 \times (d + e + f) = 12$	$NC_{C22} = PO_{C22} / PM_{C22} \times 100 = \mathbf{100\ \%}$
SECURITY LEVEL	
Score obtained: $PO_{C22} = a \times 3 + b \times 2 + c \times 1 = 36$	**Security level:**
Maximum score: $PM_{C22} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 36$	$NS_{C22} = PO_{C22} / PM_{C22} \times 100 = \mathbf{100\ \%}$

D.1. Own OHS instruction in operational electrical installations – IPSM – IEE

Table 14. **Audit criteria, Indicators, Conformity / Security Level – Sheet D.1.**

AUDIT CRITERIA							
❶ Own OHS instruction in operational electrical installations – IPSM – IEE							
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
D.1.1.–D.1.10.	10 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 30					
Total scores for questions with weight 2		b = 0					
Total scores for questions with weight 1		c = 0					
Number of questions applicable with weight 3		d = 10					
Number of questions applicable with weight 2		e = 0					
Number of questions applicable with weight 1		f = 0					
CONFORMITY LEVEL							
Score obtained: $PO_{D1} = a + b + c = 30$		**Conformity level:**					
Maximum score: $PM_{D1} = 3 \times (d + e + f) = 30$		$NC_{D1} = PO_{D1} / PM_{D1} \times 100 = \mathbf{100\ \%}$					
SECURITY LEVEL							
Score obtained: $PO_{D1} = a \times 3 + b \times 2 + c \times 1 = 90$		**Security level:**					
Maximum score: $PM_{D1} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 90$		$NS_{D1} = PO_{D1} / PM_{D1} \times 100 = \mathbf{100\ \%}$					

D.2. Specific OHS instruction for working under voltage (live work) – ISSM – LST

Table 15. **Audit criteria, Indicators, Conformity / Security Level – Sheet D.2.**

AUDIT CRITERIA							
❶ Specific OHS instruction for working under voltage (live work) – ISSM – LST							
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
D.2.1.–D.2.18.	18 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3		a = 54					

Total scores for questions with weight 2	b = 0
Total scores for questions with weight 1	c = 0
Number of questions applicable with weight 3	d = 18
Number of questions applicable with weight 2	e = 0
Number of questions applicable with weight 1	f = 0
CONFORMITY LEVEL	

Score obtained: $PO_{D2} = a + b + c = 54$	**Conformity level:**
Maximum score: $PM_{D2} = 3 \times (d + e + f) = 54$	$NC_{D2} = PO_{D2} / PM_{D2} \times 100 = \textbf{100 \%}$
SECURITY LEVEL	
Score obtained: $PO_{D2} = a \times 3 + b \times 2 + c \times 1 = 162$	**Security level:**
Maximum score: $PM_{D2} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 162$	$NS_{D2} = PO_{D2} / PM_{D2} \times 100 = \textbf{100 \%}$

D.3. Specific OHS instruction on how to complete the working under voltage (live work) authorization – ISSM – ALST

Table 16. **Audit criteria, Indicators, Conformity / Security Level – Sheet D.3.**

AUDIT CRITERIA							
❶ Specific OHS instruction OHS on how to complete the working under voltage (live work) authorization – ISSM – ALST							
Code	**INDICATOR**	**N / A**	**0**	**1**	**2**	**3**	**Weight**
D.3.1.–D.3.10.	10 indicators						
N/A – Not-applicable; 0 – Nothing; 1 - Partially (≤ 50 %); 2 - Partially (> 50 %); 3 – Completely							
Total scores for questions with weight 3	a = 30						
Total scores for questions with weight 2	b = 0						
Total scores for questions with weight 1	c = 0						
Number of questions applicable with weight 3	d = 10						
Number of questions applicable with weight 2	e = 0						
Number of questions applicable with weight 1	f = 0						
CONFORMITY LEVEL							

Score obtained: $PO_{D3} = a + b + c = 30$	**Conformity level:**
Maximum score: $PM_{D3} = 3 \times (d + e + f) = 30$	$NC_{D3} = PO_{D3} / PM_{D3} \times 100 = \textbf{100 \%}$
SECURITY LEVEL	
Score obtained: $PO_{D3} = a \times 3 + b \times 2 + c \times 1 = 90$	**Security level:**
Maximum score: $PM_{D3} = 3 \times (d \times 3 + e \times 2 + f \times 1) = 90$	$NS_{D3} = PO_{D3} / PM_{D3} \times 100 = \textbf{100 \%}$

2.3.2 General conformity level

Table 17. **General conformity level**

Sheet code	Name	Score		Confomity level
		maximum (PM)	obtained (PO)	
C. General requirements				
C.1	Minimum OHS requirements for the workplace	300	300	100 %
C.2	Minimum OHS requirements for security signs at workplace	90	90	100 %
C.3	Minimum OHS requirements for the use of work equipment by personnel	120	120	100 %
C.4	Minimum OHS requirements relating to the use of display screen equipment	27	27	100 %
C.5	Minimum OHS requirements for the use of personal protective equipment by personnel at work	18	18	100 %
C.14	Minimum OHS requirements regarding the exposure of personnel to the risks arising from electromagnetic fields	30	30	100 %
C.21	Personnel health surveillance	45	45	100 %
C.22	Measures that may be applied during periods of extreme temperatures to protect people at work	12	12	100 %
D. Specific requirements				
D.1	Own OHS instruction in operational electrical installations – IPSM – IEE	30	30	100 %
D.2	Specific OHS instruction for working under voltage (live work) – ISSM – LST	54	54	100 %
D.3	Specific OHS instruction on how to complete the working under voltage (live work) authorization - ISSM – ALST	30	30	100 %
		TOTAL		NC$_g$
		756	756	100 %

2.3. General security level for 400 kV power substation

Table 18. **General security level**

Sheet code	Name	Score		Security level	Risk level
		maximum (PM)	obtained (PO)		
A.	Employer's obligations	408	408	100 %	Small
B.	Personnel's rights and obligations	99	96	96,96 %	Small
C. General requirements					
C.1	Minimum OHS requirements for the workplace	672	672	100 %	Small
C.2	Minimum OHS requirements for security signs at workplace	249	249	100 %	Small
C.3	Minimum OHS requirements for the use of work equipment by personnel	360	360	100 %	Small
C.4	Minimum OHS requirements relating to the use of display screen equipment	60	60	100 %	Small
C.5	Minimum OHS requirements for the use of personal protective equipment by personnel at work	54	54	100 %	Small
C.14	Minimum OHS requirements regarding the exposure of personnel to the risks arising from electromagnetic fields	90	90	100 %	Small
C.21	Personnel health surveillance	132	132	100 %	Small
C.22	Measures that may be applied during periods of extreme temperatures to protect people at work	36	36	100 %	Small
D. Specific requirements					
D.1	Own OHS instruction in operational electrical installations – IPSM – IEE	90	90	100 %	Small
D.2	Specific OHS instruction for working under voltage (live work) – ISSM – LST	162	162	100 %	Small
D.3	Specific OHS instruction on how to complete the	90	90	100 %	Small

Sheet code	Name	Score		Security level	Risk level
		maximum (PM)	obtained (PO)		
	working under voltage (live work) authorization - ISSM – ALST				
		TOTAL		NS_g	NR_g
		2502	2499	99,88 %	SMALL

Table 21. **Security level / Risk level relationship**

SECURITY LEVEL	RISK LEVEL
91-100 %	Low risk
81-90 %	Medium risk
71-80 %	High risk
under 71 %	Very high risk

3. CONCLUSIONS

The paper approaches OHS measures by auditing the conformity with legal and other provisions in force, for the purpose of checking the knowledge and conformity with the legal and other provisions in force at workplace level and for assessing the effectiveness of the OHS management system.

The audit carried out is part of the initial analysis preceding the development and implementation of an OHS management system with a view to supporting management decisions, and after implementation it is used as a tool to verify the operation of the management system in order to determine the decisions required for ensuring the continuous improvement of the system. The assessment of the conformity (audit) of the 400/220 kV power substation highlighted the following:

- General conformity level for Sheet A (Employer's obligations) is 100%;
- General conformity level for Sheet B (Personnel's rights and obligations) is 97,91%;
- **General conformity level for "Management" level, for sheets A and B, is 99,53%;**
- General conformity level for Sheet C (General requirements) is 100%;
- General conformity level for Sheet D (Specific requirements) is 100%;
- **General conformity level for "Operational Personnel" level, for sheets C and D, is 100%;**
- General security level for Sheet A (Employer's obligations) is 100% - Risk level LOW;
- General security level for Sheet B (Personnel's rights and obligations) is 96,96% - Risk level SMALL;
- General security level for Sheet C (General requirements) is 100% - Risk level LOW;
- General security level for Sheet D (Specific requirements) is 100% - Risk level LOW;
- **General security level for 400/220 kV Power Substation is 99,88% - General risk level LOW,** *table 21 (Security level / Risk level relationship).*

The 400 kV Nădab power substation is found to have a general conformity level between 99,53 % and 100 % and the general safety level is 99,88 %, corresponding to a low general risk level and no critical conformity points are identified, all the safety requirements being met.

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INTEGRATE SMART HOME SYSTEMS INTO LOW-BUDGET HOUSING

ILIE UTU[1], BRANA LILIANA SAMOILA[2]

Abstract: The paper deals with some modern technologies for monitoring and conducting processes for smart buildings. It also presents a case study on the applicability of the concept of "smart home" in a "low budget" home. In principle, there are presented tangible solutions, anchored in everyday reality, which would satisfy the need for independence and freedom of modern man but also to fit into the financial reality that underlies his existence. Thus, we have tried to identify the pressing needs of each individual that can be met by a smart home, and to put them into practice taking into account the low budget we have for integrating artificial intelligence into our lives.

Keywords: smart home, control, monitoring, housing, sensor.

1. INTRODUCTION

The smart home represents a modern housing concept that integrates advanced automation and control technologies, with the purpose of increasing comfort, safety, and energy efficiency [1], [11], [16]. It allows the monitoring and control of various home systems, such as lighting, climate control, security, and energy consumption, through electronic devices and software applications.

The rapid development of information and communication technologies has led to the emergence of innovative solutions that transform traditional homes into intelligent systems capable of automatically responding to users' needs. These systems are based on sensors, [3], actuators, and programmable control units that communicate with each other through local networks or via the internet.

The implementation of the smart home concept contributes significantly to the optimization of energy consumption, the reduction of operating costs, and the increase of the safety level. Through process automation, the user can control and adjust the operation of equipment according to preferences and external conditions [12], [20].

In the current context, smart homes are becoming increasingly accessible and widespread, being used both in residential environments and in commercial or industrial buildings. The integration of these systems represents an important step toward sustainable development and the efficient use of resources[12], [22].

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The technology used for intelligent buildings may be innovative, but it necessarily relies on basic technologies. A "smart" device is equipment that, through algorithms based on logic gates, gives the impression that it can "learn" our behavior and basic needs, and, most importantly, that it does so in a personalized manner for each entity (community, neighborhood, family), and especially for each individual [13].

A smart home is a habitat—whether an apartment, office, or holiday house—that uses state-of-the-art technologies to automate systems and appliances within it [2], [8], [21]. The primary objective of a smart home is to ensure comfort, security, and utility cost savings.

Some of the characteristics of an intelligent building include the following:

• It provides data related to the performance of systems and facilities within the building.

• It monitors systems in real time and detects errors or deficiencies in building systems.

• It reports in real time and manages operations, energy consumption, and occupant comfort.

• It includes tools, technologies, resources, and systems that contribute to energy conservation and environmental sustainability.

2. IMPLEMENTATION OF A SMART HOME SYSTEM IN A LOW BUDGET HOME

The research was conducted by applying a questionnaire that provides information strictly necessary for establishing a realistic and tangible conclusion. This information refers to:

• General data: name, age category, residence (urban or rural), dwelling area, monthly income level, and budget allocated to quality of life.

• Needs for improving comfort.

Regarding lighting, [7] the options presented in the questionnaire were:

• Interior lighting to be controlled manually; automatically depending on presence in the room; automatically depending on ambient light level; centrally, with the implementation of anti-burglary scenarios.

• Lighting level to be adjusted continuously (from off to maximum) or on/off only, without continuous adjustment.

For climate control, the following aspects were of interest:

• Required functions: heating; cooling; air conditioning (air quality monitoring); underfloor heating.

• Climate control elements: traditional radiators with thermal agent; electric convector radiators; fan coil units and ventilation systems; standard air conditioning units [17].

Regarding the need for an anti-burglary and fire detection system, it was necessary to determine whether such systems should exist and whether they should operate independently [14], [19].

The method of managing commands and supervision for interior and exterior lighting, climate control, etc., had to be chosen as either local or centralized.

3. FIBARO SYSTEM FOR A STUDIO APARTMENT

The virtual house that we created is structured as follows: bathroom, kitchen and living/sleeping area.

Considering the characteristics of the living space and the limited available budget, we used a control unit with a sufficient number of connectable devices. The chosen control unit model is Home Center Lite, capable of integrating up to 230 devices. It is equipped with a Cortex A8 processor. Through its energy management function, the Fibaro Home Center Lite can monitor electricity consumption while detecting high-consumption devices [10], [15], [18].

The next step in completing the project is to enlist the sensors and other equipment at the control station (fig. 1) [4]. At the same time, the actual enrollment of each sensor to the room it serves is also done.

Fig.1. Enrolling Fibaro sensors
(http://192.168.1.100/fibaro/en/devices/)

During the programming phase, we "learned" the system to meet the requirements of the beneficiaries by implementing certain work scenarios (fig. 2).

Following the procedures outlined above, we have put into operation a minimal system, suitable for a studio of about 35 sqm.

Fig.2. Creation of scenarios
[http://192.168.1.100/fibaro/en/scenes/]

For lighting control [9] in the kitchen area (fig. 3) and the bathroom (fig. 4) we used two single switches from Fibaro, integrable in the existing architecture, without the need for additional wiring.

Fig.3. Manual operation of
lighting in the kitchen

Fig.4. Manual operation of
bathroom lighting

These switches are mounted in the device dose, connecting to the existing switches. As local actuators, in the bathroom we used a switch with a push-button switch "doorbell" and in the kitchen area we used a switch with touch control. Although the design of the latter is more attractive, we preferred not to use it in the bathroom area due to the high possibility of being operated with wet hands.

To control the lighting in the sleeping area we used a Dimmer switch 2 from Fibaro (fig. 5). It is able to adjust the light intensity according to the wishes and needs of the end customer. Using a unique algorithm, the dimmer recognizes the source of the light and calibrates it, choosing an appropriate value. In this way, we know that we use exactly the light we need for optimal energy use.

The heating system is controlled by integrating the thermostatic valve with stepper motor. Based on the cubic volume of the heated room, the Fibaro thermostat calculates how long it takes to reach the temperature we want. Moreover, the current temperature is indicated by the colour of the ring, green means a low temperature and

red the maximum temperature. This faucet also comes with a removable temperature sensor that can be placed anywhere in the room (fig. 6).

Fig.5. Manual dimmer operation
of the lighting in the bedroom

Fig.6. Automatic adjustment of
the radiator valve

To control the air conditioner, we used a digital thermostat MCO Home (fig. 7). The air conditioner is powered by a smart outlet that has control of the energy consumption [6], thus enabling us to have total control of the utility bills. When the electricity consumption exceeds the budget for that month, the outlet will cut off the power supply to the equipment by next month.

Fig.7. Automatic adjustment of the air conditioning system (A.C.)

We have integrated in the architecture of the Home Center Lite a flood sensor that alerts us to every liquid leak and a multisensor that manages to detect movement, measure temperature and light intensity (fig. 8) [5]. This sensor serves as security when we leave the house or as a control for interior lighting when required.

The application interface is as complex as it is user-friendly by incorporating all the equipment that should have been physically installed in the home into the control

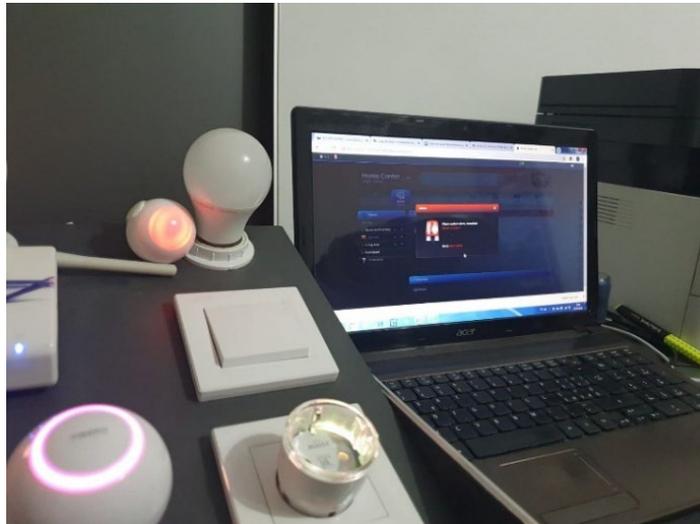screen. Thus, for the control of security systems, we have integrated a virtual numeric keypad (fig. 9).

Fig.8. Alarm triggering by the motion sensor as well as acoustic and light warning

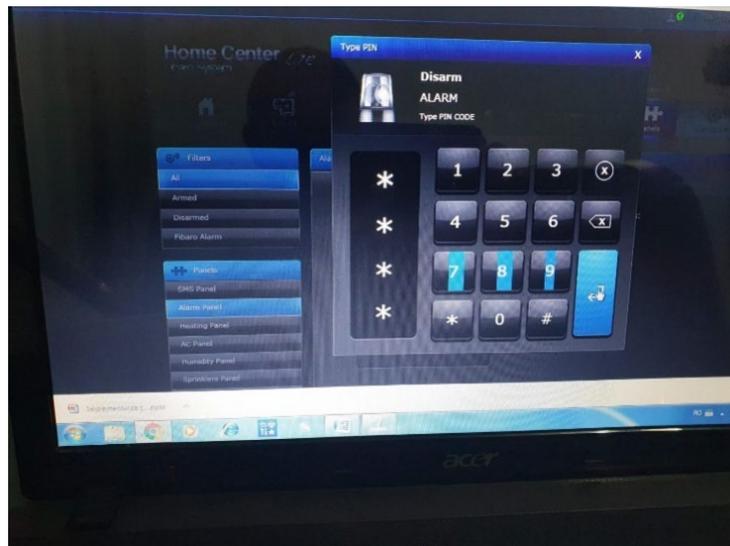**Fig.9.** Enter the disarmament code using the application interface

Regardless of the actions that appear in the foreground as acoustic or visual notification, the system imperturbably coordinates the scenarios it has programmed.

4. CONCLUSIONS

Smart home technologies represent an important step toward modern, efficient, and safe living environments. The integration of monitoring and control systems

contributes to increased comfort, reduced energy consumption, and improved security. Continuous technological advancements will further expand the capabilities of smart homes in the future.

The main purpose of the paper was a curiosity about the popularity level of the idea of "smart" housing among the low-income population, but also the realization of a "smart home" concept dedicated to them that would make them realize how close they are to the benefits that such a one offers of housing.

In order to draw some pertinent conclusions, we took the following steps:
- we studied several types of "*smart home" systems* and chose the manufacturer "Fibaro" as the best in terms of quality-price ratio and the pliability to the project we wanted to develop;
- we have developed a questionnaire dedicated to low-income people to show the needs and knowledge of the target group on the concept of "smart home";
- analyzing the answers received in the questionnaire, we designed and developed a system that lends itself to a low budget home, with the final implementation costs reaching about 1000 euros;

Following the research carried out on this subject, we have reached the following conclusions:
- the popularity level of the smart home concept is quite high among the target audience;
- there is a discrepancy between the actual costs and the ones the target group imagines regarding the implementation of this type of system, with the actual costs being much lower than they imagine;
- the main needs of the target group regarding this type of house were related to the possibility of ordering interior lighting, air conditioning systems and, last but not least, security systems.

The results of the research are in line with our expectations, the impact of the information distributed to the target group having the expected effect, namely the awareness of the real costs for the implementation of such a system.

In conclusion, the smart house concept will continue to develop alongside technological progress, becoming an essential component of future homes. The integration of artificial intelligence, IoT systems, and renewable energy sources will lead to increasingly autonomous and sustainable homes.

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OPTIMIZATION OF ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

OANA CARASCA[1]

Abstract: The increase in energy consumption in the residential sector represents a major global challenge due to rising costs and environmental impact. Energy optimization in residential buildings aims to reduce energy losses, improve system efficiency and integrate renewable energy so urces. This paper analyzes the main methods and technologies used to enhance energy efficiency in residential buildings, focusing on modern solutions applicable under current regulatory and sustainability requirements.

Key words: efficiency, residential buildings, energy consumption, building automation, renewable energy.

1. INTRODUCTION

The building sector is responsible for a significant share of global energy consumption and greenhouse gas emissions. Residential buildings account for a large portion of this consumption, mainly due to heating, cooling, lighting and the use of electrical appliances [1].

In recent years, energy optimization has become a priority, supported by European regulations promoting nearly Zero Energy Buildings (nZEB). Civil engineers play a key role in implementing technical solutions that reduce energy demand while maintaining indoor comfort and functionality.

2. ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

Energy consumption in residential buildings is primarily associated with the following systems:
- space heating and domestic hot water preparation;
- cooling and air conditioning systems;
- lighting installations;
- household appliances and electronic equipment.

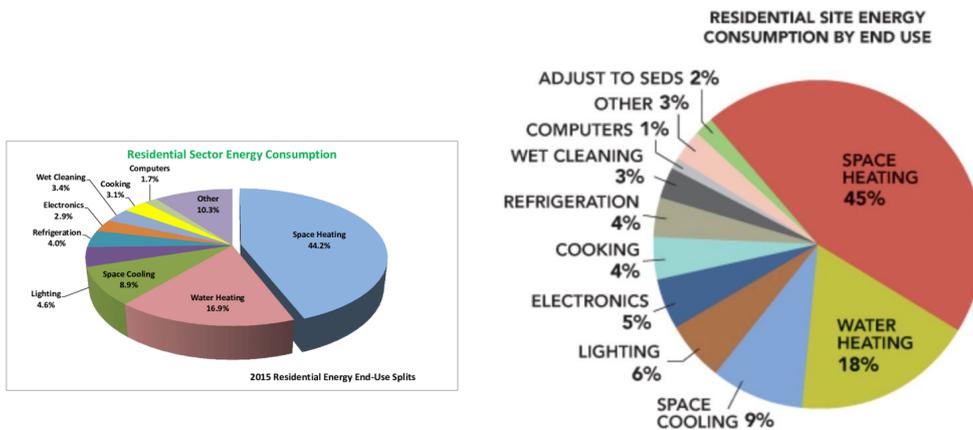[1] *Ph.D., Lecturer Eng., University of Petroşani, OanaCarasca@upet.ro*
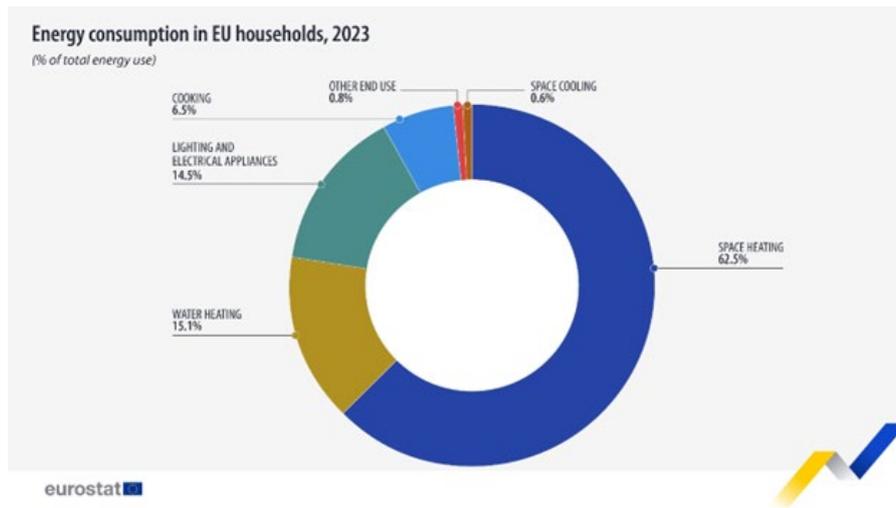
Fig.1. Main energy consumption categories in residential buildings

3. METHODS FOR ENERGY CONSUMPTION OPTIMIZATION

3.1. Improvement of the Building Envelope

Energy optimization begins with reducing heat losses through the building envelope. Effective measures include thermal insulation of external walls, roof and floors, the use of high-performance thermal windows and the elimination of thermal bridges.

These passive measures can reduce heating energy demand by up to 30–50%, depending on the initial building condition [3].

The energy performance of buildings is significantly influenced by the quality of the building envelope. Improving the envelope represents an effective solution for reducing energy consumption, enhancing thermal and acoustic comfort, and extending

the service life of buildings. This paper presents the main strategies for improving building envelopes, the materials used, insulation methods, and thermal bridge control techniques, as well as their impact on energy efficiency and building sustainability. Implementation challenges and future development perspectives are discussed in the context of the European regulatory framework for nearly zero-energy buildings (NZEB).
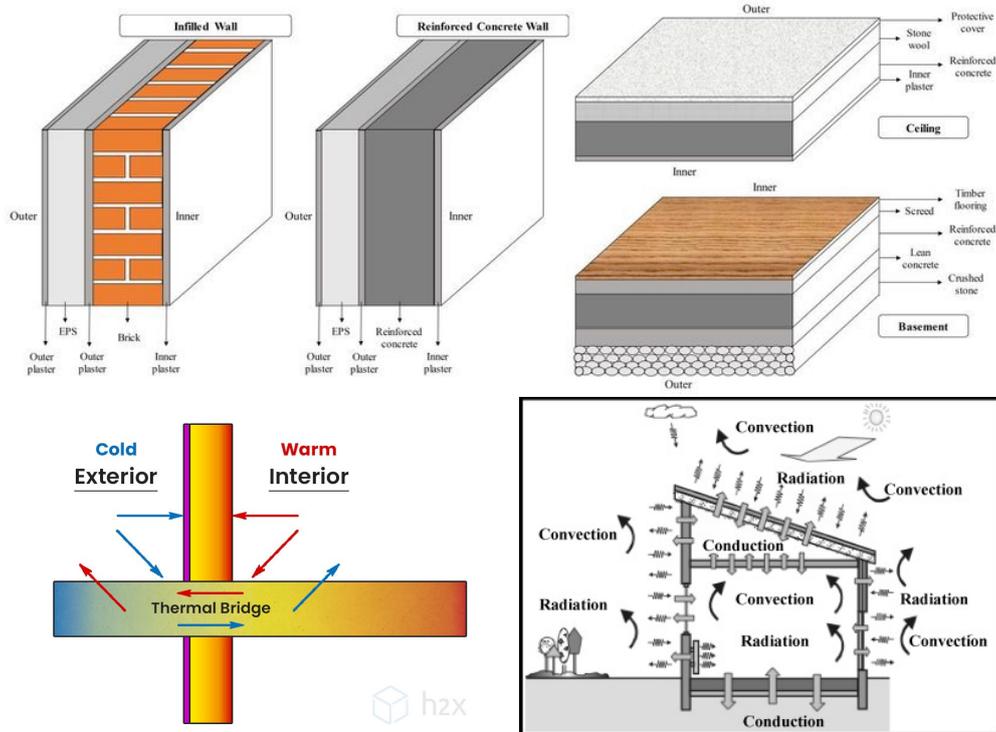

Fig.2. Building envelope improvement measures for energy efficiency

The building envelope represents the external layer that separates the indoor environment from outdoor conditions and plays a crucial role in controlling energy and mass transfer. In the field of civil engineering, the energy efficiency of a building is directly related to the thermal and acoustic performance of its envelope. In the context of increasing energy costs and stricter environmental regulations, improving the building envelope has become a necessity for reducing energy losses, ensuring structural protection, and enhancing occupant comfort.

a). Objectives of Building Envelope Improvement:

The main objectives pursued through building envelope modernization are:

1. Reduction of heat losses during the cold season and limitation of heat gains during summer.

2. Improvement of thermal and acoustic comfort within the building.

3. Extension of structural durability by protecting the building against moisture, condensation, and weather exposure.

4. Reduction of environmental impact through decreased energy consumption and lower CO_2 emissions.

b). Methods for Improving the Building Envelope:

✓ **Thermal Insulation:**

• Internal insulation is achieved by applying thermal insulation materials to the interior side of walls. This solution preserves the exterior appearance of the building but reduces usable interior space.

• External insulation (ETICS – External Thermal Insulation Composite Systems) involves installing insulation boards on the façade, covered with decorative plaster, thereby preventing thermal bridges and protecting the building structure.

• Roof and floor insulation is carried out using mineral wool, expanded or extruded polystyrene, or polyurethane foam.

✓ **Thermal Bridge Control:**

Thermal bridges are critical areas where heat transfer is intensified. They commonly occur at corners, structural joints, and around window openings. Mitigation solutions include:

• Thermally insulated window frames and profiles.

• Additional insulation at corners and joints.

• Prefabricated elements with optimized thermal performance.

✓ **High-Performance Windows and Doors:**

• Windows with insulating glazing units consisting of double or triple panes filled with inert gas.

• Frames made of PVC, laminated wood, or aluminum with thermal break.

•Airtight seals to prevent air infiltration.

✓ **Ventilation and Airtightness:**

•Vapor diffusion membranes to prevent condensation.

• Mechanical ventilation systems with heat recovery (HRV).

• Careful sealing of joints and gaps to enhance energy efficiency.

Materials Used:

The main modern materials used to improve building envelopes include:

• Expanded polystyrene (EPS) and extruded polystyrene (XPS) – good thermal insulation properties and moisture resistance.

• Basalt and glass mineral wool – effective acoustic insulation and fire resistance.

• Polyurethane foam (PUR/PIR) – spray-applied, adaptable to irregular surfaces.

• Innovative materials, such as aerogels and phase-change materials for thermal energy storage.

c). Benefits of a High-Performance Building Envelope:

• Reduction of energy consumption by 30–50%.

• Increased occupant comfort through stable indoor temperatures and improved sound insulation.

• Prevention of mold formation and structural degradation.

• Increase in the market value of the building.

• Contribution to sustainability goals and compliance with NZEB requirements.

d). Challenges and Future Perspectives:

The implementation of building envelope improvement technologies may be limited by:

• High initial investment costs.

• Compatibility issues with existing structures, particularly historic buildings.

• The need for accurate design to prevent condensation-related problems.

• Appropriate material selection based on climatic zone and environmental exposure.

Future perspectives include the use of materials with superior thermal performance, the integration of renewable energy solutions, and the development of smart buildings with adaptive envelopes that automatically respond to external conditions and building energy demands.

Conclusions:

Improving the building envelope represents a key strategy for enhancing energy efficiency, comfort, and durability in civil engineering constructions. Proper material selection, effective thermal bridge control, and the optimization of windows and doors significantly contribute to improved thermal and acoustic performance. In the context of modern regulations and sustainability objectives, building envelope modernization constitutes a strategic step toward the development of energy-efficient and durable buildings.

3.2. Efficient Heating and Cooling Systems

The use of modern heating and cooling systems significantly contributes to energy savings. Common solutions include air-to-water and ground-source heat pumps, condensing boilers, ventilation systems with heat recovery and high-efficiency air conditioning units [4].

Ventilation Systems with Heat Recovery:

Ventilation systems with heat recovery play a crucial role in ensuring adequate indoor air quality while minimizing energy losses in modern buildings. These systems are particularly important in energy-efficient and airtight constructions, where natural infiltration is insufficient to meet ventilation requirements.

A heat recovery ventilation (HRV) system operates by supplying fresh outdoor air to interior spaces while simultaneously extracting stale indoor air. The defining characteristic of such systems is the presence of a heat exchanger, which enables the transfer of thermal energy from the exhaust air stream to the incoming supply air without mixing the two airflows. As a result, a significant portion of the thermal energy that would otherwise be lost through ventilation is recovered.

During the heating season, the warm exhaust air transfers heat to the colder incoming air, thereby preheating it before it enters the occupied spaces. Conversely, during the cooling season, the process helps reduce the cooling load by transferring

heat from the incoming warm air to the cooler exhaust air. Modern heat exchangers, particularly counterflow and cross-counterflow designs, can achieve heat recovery efficiencies ranging from 60% to over 90%, depending on system configuration and operating conditions.

Two main categories of heat recovery ventilation systems are commonly used: heat recovery ventilators (HRV) and energy recovery ventilators (ERV). HRV systems recover only sensible heat, whereas ERV systems also allow for the transfer of latent heat, enabling partial moisture exchange between the air streams. Consequently, HRV systems are generally more suitable for cold or temperate climates, while ERV systems are preferred in warm or humid regions where indoor humidity control is essential.

The implementation of ventilation systems with heat recovery offers multiple benefits. From an energy perspective, these systems significantly reduce heating and cooling demand, contributing to lower operational energy consumption and compliance with nearly zero-energy building (NZEB) requirements. From an indoor environmental quality standpoint, continuous mechanical ventilation ensures the removal of carbon dioxide, volatile organic compounds, excess moisture, and odors, thereby enhancing occupant health and comfort. Furthermore, by controlling indoor humidity levels, these systems reduce the risk of condensation and mold formation, contributing to improved building durability.

Despite their advantages, the effectiveness of heat recovery ventilation systems depends strongly on proper design, installation, and operation. Key factors include adequate airtightness of the building envelope, correct airflow rates, balanced supply and exhaust volumes, well-insulated ductwork, and regular maintenance of filters and mechanical components. Inadequate design or poor installation may result in reduced efficiency, increased noise levels, or compromised indoor air quality.

In conclusion, ventilation systems with heat recovery represent a fundamental component of modern energy-efficient building design. By combining controlled ventilation with high energy performance, these systems support sustainability objectives, enhance indoor environmental quality, and extend the service life of building components. Their integration is therefore essential in contemporary civil engineering practice, particularly in low-energy and nearly zero-energy buildings.
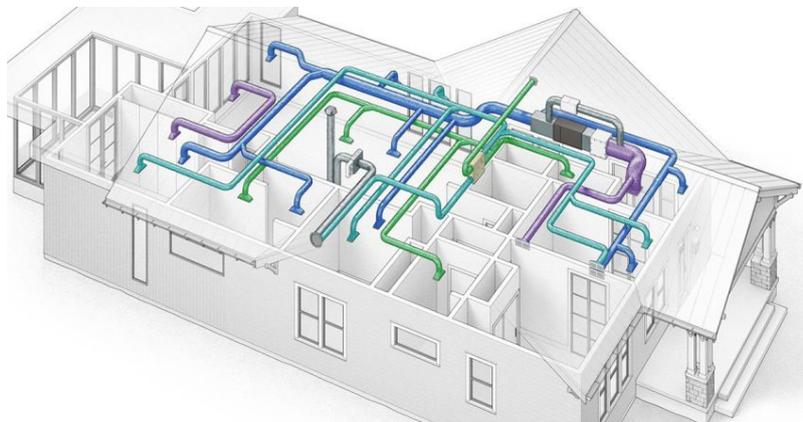
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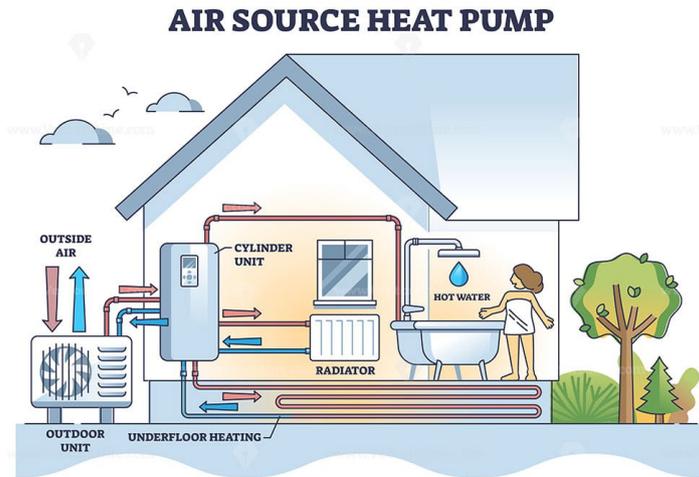
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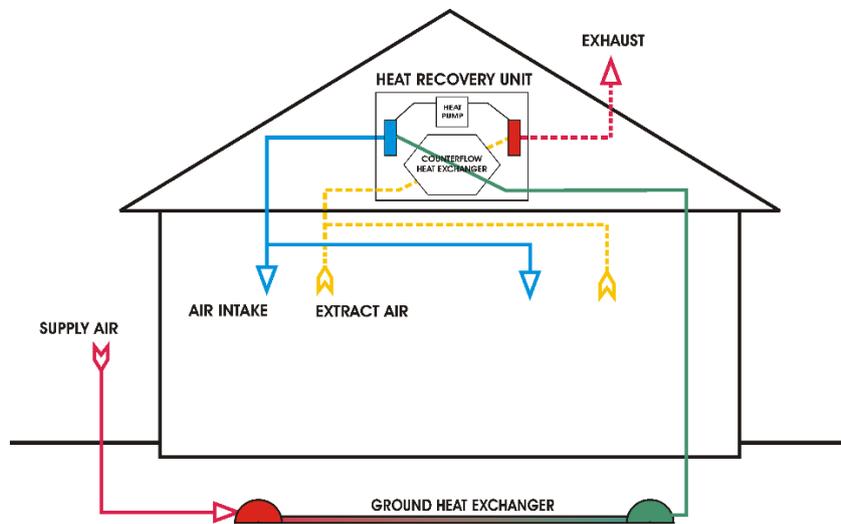
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Fig.3. Efficient heating, cooling and ventilation systems in residential buildings

3.3. Energy-Efficient Lighting

Replacing conventional lighting systems with LED technology, combined with presence sensors and automatic daylight control, leads to substantial energy savings. Energy consumption for lighting can be reduced by up to 70% using modern control solutions [5].

3.4. Building Automation and Smart Systems

Smart Home and Building Management Systems enable automatic control of lighting, heating and cooling based on occupancy and predefined schedules. These systems rely on sensors, controllers and IoT technologies, allowing real-time monitoring and optimization of energy use [6].
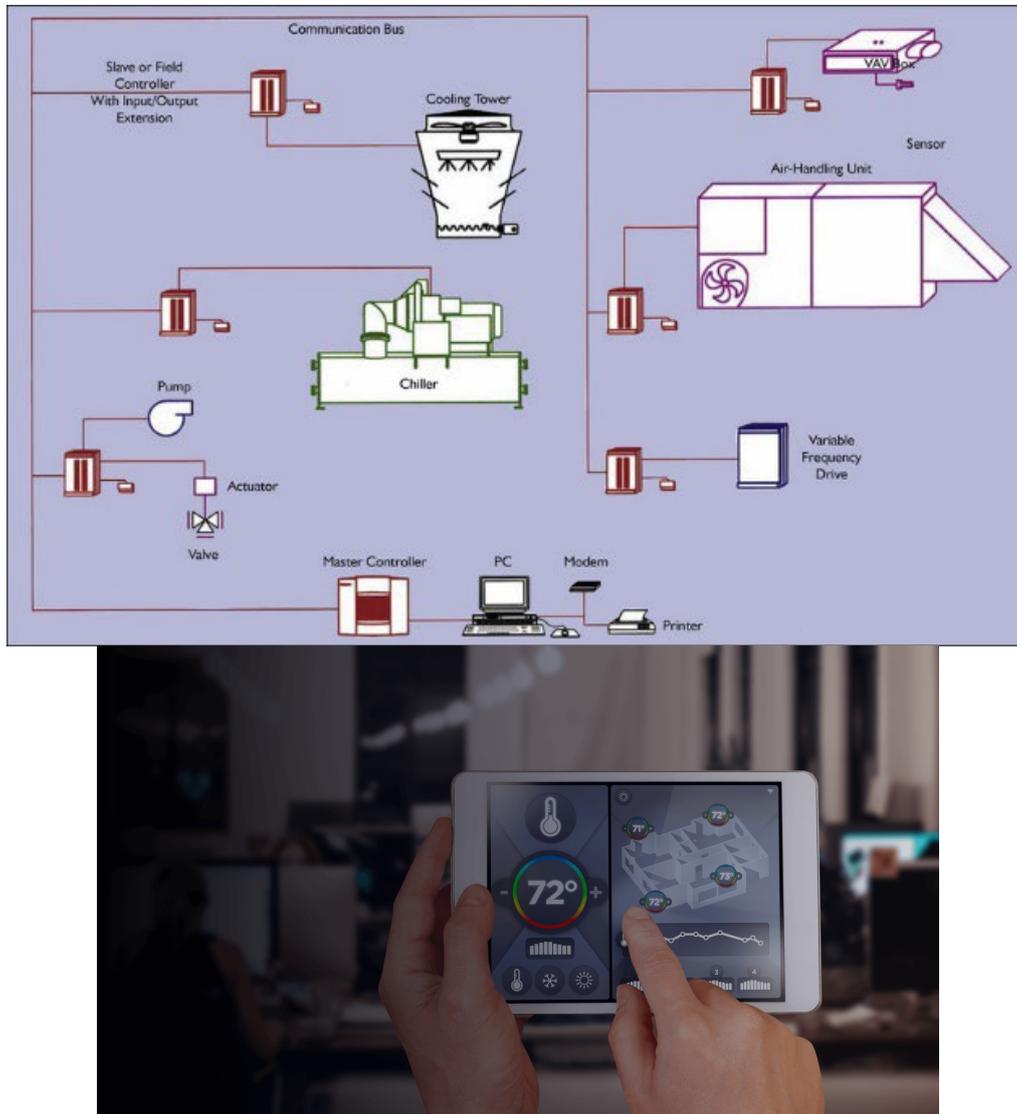

Fig.4. Smart Home system architecture for energy optimization

3.5. Integration of Renewable Energy Sources

Renewable energy systems play an essential role in reducing dependence on conventional energy sources. Photovoltaic panels, solar thermal collectors and hybrid grid-connected systems contribute to lower CO_2 emissions and reduced operating costs [7].

4. MONITORING AND ANALYSIS OF ENERGY CONSUMPTION

Energy monitoring is performed using energy meters, sensors and data acquisition systems connected to software platforms. Continuous monitoring allows the identification of inefficiencies and supports data-driven decision-making for energy optimization [8].

5. CASE STUDY: ENERGY OPTIMIZATION IN A RESIDENTIAL BUILDING

5.1 Building Description

The case study analyzes a multi-family residential building equipped with thermal insulation, LED lighting, a heat pump system and a basic Smart Home solution for energy monitoring.

5.2 Results and Discussion

The implementation of passive and active measures resulted in an overall energy consumption reduction of approximately 35%, with improved thermal comfort and lower operational costs.

Fig.5. Energy consumption before and after optimization – case study

6. BENEFITS OF ENERGY CONSUMPTION OPTIMIZATION

Optimizing energy consumption in residential buildings provides multiple benefits, including reduced operating costs, improved indoor comfort, lower environmental impact, increased property value and compliance with current regulations.

7. CONCLUSIONS

Energy consumption optimization in residential buildings represents a key strategy for sustainable development. By combining passive measures, efficient technologies and intelligent control systems, significant energy savings can be achieved. The integration of renewable energy sources further enhances building performance and contributes to environmental protection and improved quality of life.

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HOLISTIC RISK ASSESSMENT FOR NATIONAL POWER GRID FACING EXTREME WEATHER EVENTS AND NATURAL HAZARDS

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Abstract: National Power Grid are increasingly exposed to extreme weather events and natural hazards whose frequency, intensity, and unpredictability have grown under changing climatic conditions. Traditional risk assessment methods – often focused on individual assets or isolated hazard types – are no longer sufficient to capture the complex, interconnected vulnerabilities of modern power networks. This study proposes a holistic risk assessment framework that integrates multi-hazard characterization, systemwide vulnerability analysis, and probabilistic impact modeling to evaluate the resilience of national-scale power infrastructures. The framework considers cascading failures, interdependencies with other critical sectors, spatial variations in infrastructure exposure, and the dynamic adaptation of grid operations. Using recent extreme weather events and geophysical hazards as case studies, the analysis reveals key system weaknesses and prioritizes resilience-enhancing interventions. The results demonstrate the importance of comprehensive risk metrics and cross-sector coordination in guiding national energy policy, infrastructure investment, and emergency preparedness. Ultimately, the proposed approach supports decision-makers in strengthening the robustness and adaptability of power systems facing an evolving landscape of natural hazards.

Keywords: risk assessment, National Power Grid, extreme weather, natural hazard.

1. INTRODUCTION

National Power Grid (NPG) form the backbone of modern societies, enabling essential services such as healthcare, transportation, communication, and industrial operations [26], [29]. However, these systems are increasingly challenged by extreme weather events – including heatwaves, storms, floods, droughts, and wildfires – as well

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as geophysical hazards such as earthquakes, landslides, and volcanic activity [15], [18], [23]. Climate change has intensified many of these hazards, amplifying their impacts and complicating long-term planning for infrastructure resilience. As disruptions to power systems can propagate rapidly through interconnected networks, even localized events may trigger widespread outages and economic losses [7], [10], [16], [22].

Historically, risk assessments for power systems have relied on deterministic models or single-hazard evaluations that do not fully capture the complexity of real-world conditions [32], [34]. Such approaches overlook key factors such as compound hazards, interdependencies with other critical infrastructures (e.g., water supply, telecommunications, gas networks), and the nonlinear behavior of grid components under stress. Recent large-scale outages – from hurricanes and polar vortices to severe flooding and wildfires – have illustrated the need for a more integrated perspective.

A holistic risk assessment approach addresses these challenges by combining physical hazard modeling, infrastructure vulnerability analysis, system operation dynamics, and probabilistic risk estimation [24]. This multidimensional perspective enables the identification of not only direct physical risks but also operational, organizational, and cascading risks within and beyond the power sector. Moreover, it supports scenario analysis, enabling policymakers and planners to evaluate potential future climates, evolving demand patterns, and emerging technologies such as distributed energy resources and smart-grid controls [11], [14], [17], [33].

This paper presents a comprehensive framework for holistic risk assessment tailored to national-scale power systems. The approach integrates multi-hazard exposure mapping, advanced vulnerability modeling, and system-level impact analysis with decision-oriented risk metrics [21], [25], [27]. Through empirical case studies and model simulations, we demonstrate how the framework can guide strategic planning, enhance emergency response capacities, and inform long-term investments in resilient infrastructure. By adopting holistic, data-driven methodologies, nations can better prepare for the growing threats posed by extreme weather events and natural hazards, ensuring reliable and sustainable power supply in an increasingly uncertain world [28].

The NPG from National Power System, functions as an interconnected system to the European Power System – ENTSO-E, which represents the European Network of Transmission System Operators for Electricity [12], [13], [19], [31].

Romania, through the national electricity transmission company, Transelectrica, which is a national transmission and system operator (TSO), has an active and essential role within ENTSO-E, being a full member [20]. It manages and operates the electricity transmission system, ensuring electricity exchanges between Romania and the countries of the European Union and the neighbouring countries that are not part of the European Union (Serbia, Ukraine and the Republic of Moldova) [].

The NPG, is composed of the following critical energy infrastructures, fig.1:

- *82 power substations:* 1 power substation in a gauge of 750 kV, but functioning at 400 kV; 38 power substations of 400 kV; 43 power substations of 220 kV [35];
- *8834.4 km overhead power lines:* 3.1 km – 750 kV; 4915.2 km – 400 kV; 3875.6 km – 220 kV;40.4 km – 110 kV (interconnection Serbia, Ukraine and the Republic of Moldova) [30];

- *216 transformation units totaling 38 058 MVA;*
- *1 National Energy Dispatch – NED;*
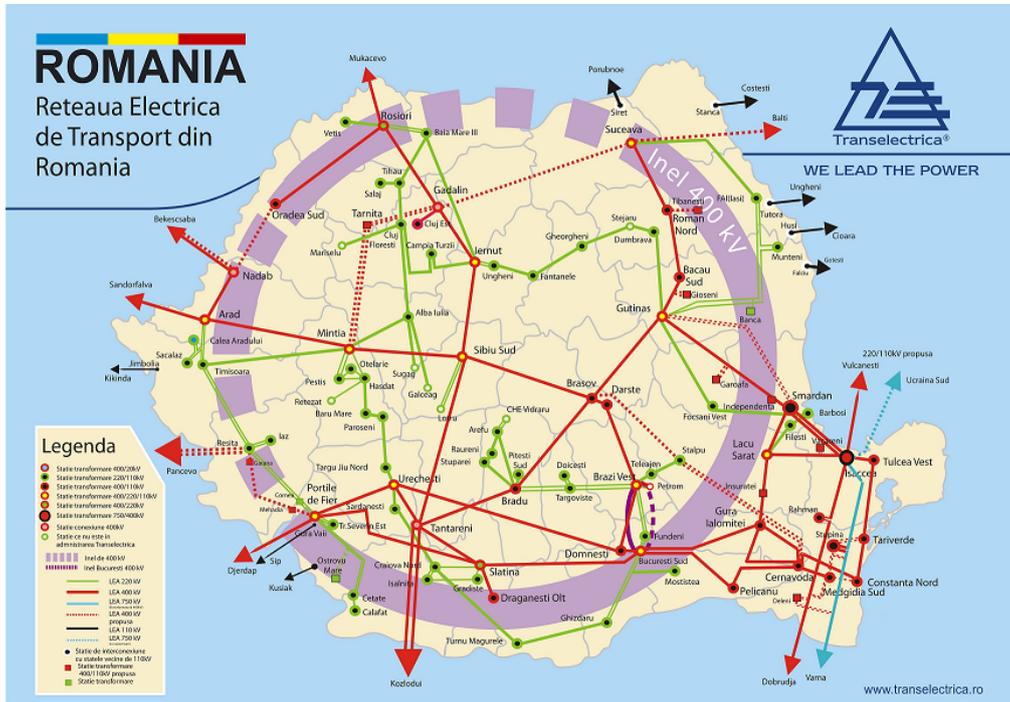- *5 Territorial Dispatchers – TED* [1], [2], [3].

Fig.1. National Power Grid map (source: Transelectrica)

2. ASSESSMENT AND MANIFESTATION

2.1. Extreme weather events

The identification, assessment and manifestation are shown in Table 1 [4], [5], [6], [36].

Table 1. **Extreme weather events**

Risk scenario: EXTREME WEATHER EVENTS			
1	Extreme low temperature (cold)		• Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, this causes the limitation or total loss of reserves; • In conditions of very low temperatures, accidental events occur that lead to the unavailability of equipment in the transmission and distribution network;
		Likelihood	3 Medium
		Gravity/ Impact	5 Very high
		Risk level	15
		Scenario type	13– 16 Bad

			- Under these conditions, interconnection capacities are required to the maximum, which can limit the level of electricity imports; - Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers; - Low production in certain plants leads to large power movements to deficient areas, overload of some grid elements and results in voltage deviations and difficulties in compensating reactive power; - For certain time intervals problems arise in ensuring that the N-1 safety criterion is met. - Low production level and loading of certain lines can lead to the impairment of the static and dynamic stability of the NPS; - The impossibility of intervention in some areas appears and increases the time needed for intervention and remediation actions; - In conditions of extreme low temperatures, accidental triggers of electrical equipment (power lines, transformers or autotransformers) may occur, which may lead to the overload of other equipment and to the increase of grid congestions; - There is a risk of the impossibility of operating some switching equipment, in the event of interventions or maneuvers necessary to maintain the safe functioning of power grids;

			• There is a high media pressure, as well as from the public opinion and the political environment, regarding the rapid resolution of the crisis situation and the provision of energy needs for the population and the stopping of exports; • The low temperature can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • In conditions of insufficient production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
2	Storm	Likelihood: 3 Medium Gravity/Impact: 5 Very high Risk level: 15 Scenario type: 13–16 Bad	• Line triggers occur due to electrical discharges, conductor breaks, trees falling on lines, conductor galloping; • The triggers can be simultaneous for lines located on the same corridor, the same pillars or on lines located very close together; • Damage to insulators, conductors or falling trees can lead to long-term unavailability of lines; • Some pillars may fall due to the galloping phenomenon; • Triggers occur in substations due to faults in busbar fields

			caused by materials/branches brought by the wind; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Production in wind power plants is deacreasing sharply due to wind intensification; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
3	Heavy rainfall and flooding	Likelihood — 3 Medium Gravity/Impact — 5 Very high Risk level — 15 Scenario type — 13–16 Bad	• Equipment triggers occur due to flooding of substations; • Triggers or unavailability of some lines occur, caused by landslides or floods affecting the stability of the pillars; • There is a reduction in production in the affected hydro power plants; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Problems arise in supplying

			• some grid areas for a very long period, correlated with the time required to repair/replace damaged infrastructures; • Congestions can occur on interconnection lines and even the impossibility of securing electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
4	Winter weather conditions (snow, ice, frost)	Likelihood: 3 Medium Gravity/ Impact: 5 Very high Risk level: 15 Scenario type: 13– 16 Bad	• Several line triggers occur, caused by snow, ice or frost, or falling trees on the lines; • Production in wind power plants is decreasing or stopping altogether due to ice deposits on turbine blades; • Damage to insulators, conductors or falling trees can lead to long-term unavailability of lines; • Some pillars may fall due to the galloping phenomenon; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged infrastructures; • Large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • There is a risk of extensive

			damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
5	Heat wave	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• Line triggers occur due to the expansion of OHL conductors, equipment triggers due to sealing faults (oil/SF6 gas leaks), incorrect functioning of numerical terminals due to excessive heating of switchbox, shutdown of computer and process systems and communication systems; • Vegetation fires may occur in transformer substations correlated with the production of short circuits in the grid and by melting some materials when passing the fault current through equipment with imperfect contacts; • Vegetation fires may occur in the safety corridor of power lines, leading to equipment triggers or damage; • At peak times, the energy consumption from internal resources is not covered and it is necessary to import a significant amount of energy. Under these conditions, interconnection capacities which may limit the level of electricity imports are maximised; • The appropriate level of voltage in certain grid areas is not ensured due to a reactive power deficit caused by the widespread use of air conditioners (coolers); • Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, which causes the limitation or total loss of reserves;

				• Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers; • Reduced production in certain plants leads to large power movements to deficient areas and results in voltage deviations and difficulties in compensating reactive power; • For certain time intervals problems arise in ensuring that the N-1 safety criterion is met; • The low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS; • The drought can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
6	Drought	Likelihood	3 Medium	• At peak times, the energy consumption from internal resources is not covered and it is necessary to import a significant amount of energy. Under these conditions, interconnection capacities
		Gravity/ Impact	5 Very high	
		Risk level	15	
		Scenario type	13– 16 Bad	

			which may limit the level of electricity imports are maximised; • The appropriate level of voltage in certain grid areas is not ensured due to a reactive power deficit caused by the widespread use of air conditioners; • Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, which causes the limitation or total loss of reserves; • Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers; • Reduced production in certain plants leads to large power movements to deficient areas and results in the overload of some grid elements and voltage deviations and difficulties in compensating reactive power; • For certain time intervals problems arise in ensuring that the N-1 safety criterion is met; • Low production level and loading of certain lines can lead to the impairment of the static and dynamic stability of the NPS; • The drought can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and

			even the impossibility of ensuring electricity exports; • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. • Under the action of heat, accidental triggers of electrical equipment (power lines, transformers or autotransformers) may occur, which may lead to the overload of other equipment and to the increase of grid congestions;
7	Forest /vegetation fires	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• Large areas are covered by fires, and in certain areas violent storms are produced, accompanied by electric discharges that increase the number of fire outbreaks; • Line triggers occur, caused by fire flames and line disconnections are required to allow staff to intervene to extinguish or stop the spread of fires; • Fires can also spread across substation territory leading to equipment triggers and damage; • There is a reduction in production in wind power plants due to wind intensification; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of affected/damaged equipment; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying

			some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.

2.2. Natural hazards

The identification, assessment and manifestation are shown in Table 2 [7-9]

Table 2. **Natural hazards**

Risk scenario: NATURAL HAZARDS			
1	Solar storm	Likelihood — 1 Very low Gravity/ Impact — 5 Very high Risk level — 5 Scenario type — 4– 6 Low	• The solar (geomagnetic) storm generates the appearance of the Carrington effect, which leads to widespread damage to transformer units and line insulators; • Protection malfunctions occur; • All computer systems are affected; • Major and long-term disturbances occur in communication systems that significantly hinder the response in a crisis situation; • Equipment triggers take place and some equipment becomes unavailable for a very long period of time; • Controlled disconnects occur to prevent the transformation units from being overloaded; • A controlled blackout may occur due to the evolution at European level; • Coordinated action is taken at ENTSO-E level as the situation has been anticipated and some organizational crisis response measures have been taken.

			• Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets;
2	Earthquake	<table><tr><td>Likelihood</td><td>1 Very low</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>5</td></tr><tr><td>Scenario type</td><td>4– 6 Low</td></tr></table>	• Damage/ triggers of equipment in substations and damage/falls of pillars on lines occur; • Accidental shutdowns of production groups in power plants located in the area affected by the earthquake may occur; • Industrial accidents may occur accompanied by fires, production shutdowns, gas emissions or leaks of hazardous substances; • Damage occurs to GIS buildings in power substations, electrical equipment foundations or transformers; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of lines and transformation units; • The functioning of communication systems is disrupted due to the phenomenon of generalized panic; • Rescue or fire fighting teams are required; • Difficulties may arise in carrying out faults remediation work in substations, caused by the large number of equipment of the same type affected and the lack of equipment in security stocks; • Problems arise in ensuring that the N-1 safety criterion is met;

		• Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged assets; • Congestions can occur on interconnecting lines and even the impossibility of securing electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.

2.3. Risk scenarios estimation and assessment algorithm

2.3.1. Likelihood Estimation

LEVEL	LIKELIHOOD	Time
1. Very low	It has a very low likelihood of occurring. Normal measures are required to monitor the evolution of the event.	over 20 years
2. Low	The event has a low likelihood of occurring. Efforts are needed to reduce the likelihood and/or mitigate the impact produced.	16 – 20 years
3. Medium	The event has a significant likelihood of occurring. Significant efforts are needed to reduce the likelihood and/or mitigate the impact produced.	11 – 15 years
4. High	The event has a likelihood of occurring. Priority efforts are needed to reduce the likelihood and mitigate the impact produced.	6 – 10 years
5. Very high	The event is considered imminent. Immediate and extreme measures are required to protect the objective, evacuation to a safe location if the impact so requires.	1 – 5 years

2.3.2. Gravity Estimation

LEVEL	GRAVITY / IMPACT
1. Very low	The event produces a minor disturbance in the activity, without material damage
2. Low	The event causes minor material damage and limited disruption to activity
3. Medium	Injuries to staff, and/or certain losses of equipment, utilities and delays in providing the service.
4. High	Serious staff injuries, significant loss of equipment of installations and facilities, delays and/or interruption of service provision.

	5. Very high	The consequences are catastrophic resulting in deaths and serious injuries to staff, major losses in equipment, installations and facilities and termination of service provision.

2.3.3. Risk Level Calculation

LIKELIHOOD	Very high 5					
	High 4					
	Medium 3					
	Low 2					
	Very low 1					
	0	Very low 1	Low 2	Medium 3	High 4	Very high 5
		GRAVITY / IMPACT				

Note: The risk is given by the product between Likelihood and Gravity / Impact

2.3.4. Risk Scenario Type

Risk level: 1 – 3	Risk level: 4 – 6	Risk level: 7 – 12	Risk level: 13 – 16	Risk level: 17 – 25
Very low	Low	Moderate	Bad	Very bad

3. CONCLUSIONS

Integrated Risk Perspective is Essential – A holistic risk assessment demonstrates that evaluating the national power grid solely from an engineering or operational standpoint is insufficient. Extreme weather events and natural hazards require integration of meteorological, geological, infrastructural, and socio-economic data to fully understand vulnerabilities and interdependencies. **Critical Vulnerabilities Identified** – The assessment reveals that key components – such as transmission lines, substations, and distribution networks—are particularly susceptible to high-impact events like hurricanes, floods, heatwaves, and earthquakes. Cascading failures from a single point of vulnerability can result in widespread outages, highlighting the need for strategic redundancy;

Dynamic and Probabilistic Approaches Improve Resilience – Traditional deterministic assessments are inadequate in capturing the uncertain nature of extreme events. Incorporating probabilistic risk models allows for scenario-based planning, enabling grid operators to anticipate a range of potential threats and prioritize mitigation measures effectively. **Interdependency with Other Critical Infrastructures** – The study underscores that the power grid does not operate in isolation; disruptions can cascade to water supply, telecommunications, transportation, and healthcare. Holistic assessment must therefore account for cross-sector dependencies to prevent systemic failures.

Preventive and Adaptive Measures Are Key – Risk mitigation strategies, such as grid hardening, decentralized energy systems, smart grid technologies, and emergency response planning, are critical. Investments in early warning systems and adaptive infrastructure significantly reduce both the likelihood and impact of power outages during extreme events. **Policy, Planning, and Stakeholder Engagement** – Effective risk management requires coordination among government agencies, utility companies, and local communities. Policies supporting infrastructure resilience, real-time data sharing, and climate-informed planning are crucial for enhancing national energy security. **Continuous Monitoring and Updating of Risk Assessments** – Climate change and evolving hazard patterns mean that past risk assessments may become obsolete. A dynamic, continuously updated risk management framework ensures the power grid remains resilient against emerging threats.

A holistic risk assessment reveals that safeguarding a national power grid against extreme weather and natural hazards requires an integrated, proactive, and adaptive strategy. By combining engineering solutions, probabilistic risk modeling, cross-sector collaboration, and policy support, national energy infrastructure can achieve resilience, reliability, and sustainability in the face of growing environmental uncertainties.

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THE IMPACT OF THE REVERSE CIRCULATION EFFECT IN ELECTRICAL NETWORKS

MARIA DANIELA STOCHIŢOIU[1], ILIE UŢU[2]

Abstract. The traditional electricity grid was designed to ensure a one-way flow of energy, from generation (production) to consumption, through transmission and distribution networks. However, as global energy demand evolves, traditional systems are changing their dynamics to integrate more and more renewable energy sources.

Key words: power flow, renewable energy sources, energy transition

1. INTRODUCTION

The growing focus on reducing environmental pollution from electricity generation, along with the need to use energy more efficiently, has encouraged a wider implementation of renewable energy sources. These include both natural resources such as wind and solar power, as well as residual heat from thermal processes, all aimed at minimizing environmental impact.

A rational balance is needed between expanding renewable energy sources - whose output cannot be fully controlled - maintaining the security of the energy system, and limiting the land allocated for renewable installations so as to avoid reducing agricultural areas essential for food production (the food–energy conflict).

Generating electricity is a process that produces considerable polluting emissions, more around of power plants. Expanding the use of renewable energy sources, which have very low operational emissions, offers an effective way to reduce pollution. Primary energy resources such as solar, wind, hydro, or geothermal energy do not generate pollutants during their conversion into electricity, are practically inexhaustible, and - when combined with energy storage systems - can also be treated as controllable sources.[1]

Integrating renewable energy sources into the power system significantly influences its performance, particularly when done on a large scale, and introduces risks due to the unpredictable nature of their output. Sudden drops or interruptions in production can create challenges in maintaining system stability. The use of energy storage systems enables better control of these sources by smoothing out fluctuations

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caused by weather-dependent generation. When managed intelligently, renewable energy can offer substantial benefits to users who operate such systems [3], [4].
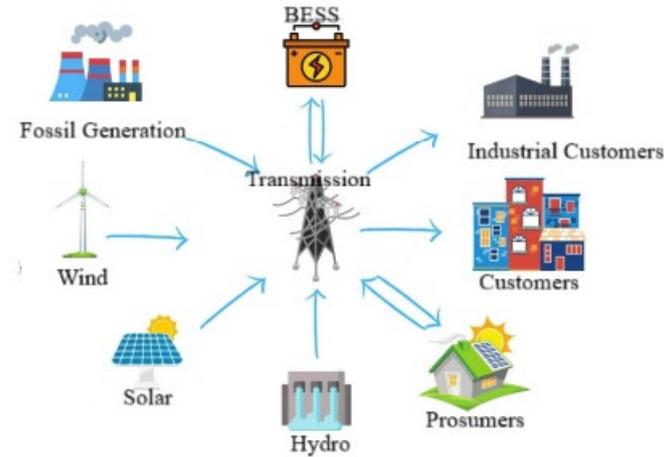
Fig.1 The structure of future energy transmission

The goal of lowering energy costs by reducing consumption from the public grid has encouraged many consumers to install renewable sources (typically solar) along with storage solutions. Effective active power regulation and source flexibility are crucial for ensuring the successful commercial integration of these systems.

The variability of primary energy sources, taking into account the uncontrollable aspect of the energy supply of weather-dependent sources as well as the variability of the usage curve, determines that the existence of electrical energy storage systems is of particular interest for controlling the functioning of the energy system.[5]

2. THE REVERSE POWER FLOW

The process of integration and interconnection of DG into existing power systems is complex, involving technical challenges regarding power quality and protection, functional challenges regarding load balancing, regulatory challenges regarding equitable access, and political challenges encouraging action to achieve societal objectives. However, the benefits of DG, such as the ability to harness RES, many of which are naturally dispersed, make it essential for their widespread adoption in the relatively near future. [1],[3], [12]

Especially during summer midday hours, when solar irradiance peaks and the demand from consumers connected to low- and medium-voltage networks is low, PV installations can generate a reverse power flow, as the consumption in these networks may fall below the power produced by the photovoltaic systems. The use of energy storage solutions by active users can help counteract and reduce this effect.

Because distribution networks are originally designed for one-way power flow, the voltage gradually decreases with distance from the generator toward the transformer. These voltage drops are predictable and are factored into the network's

design to ensure that voltage stays within acceptable limits under normal operating conditions. However, when a distributed generation (DG) unit is added, the direction of current flow changes—or can even reverse—causing the voltage to rise in ways that are harder to anticipate. Meeting voltage limit requirements therefore imposes constraints on the amount of DG capacity that can be connected to the grid, especially at low-voltage levels [4], [11].
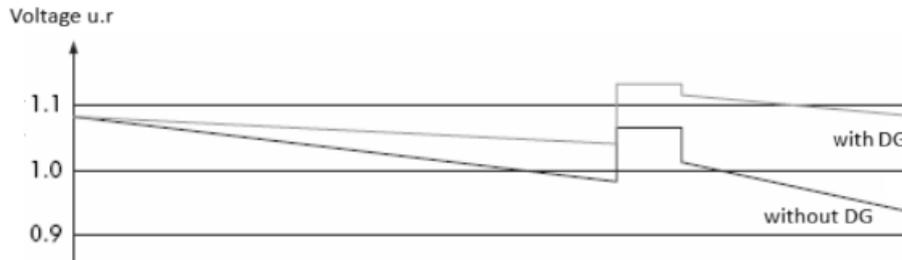
Fig.2 Voltage increase due to reversal of power flow due to DG

In the same time with the increase the number of sources connected via frequency converters, it becomes necessary to develop artificial inertia schemes that provide the necessary support for limiting the rate of change of and improving the dynamic stability conditions of the system. With the increase in the share of energy produced from renewable sources, their effects on the quality of electricity must be taken into account: the occurrence of voltage harmonics, electrical current imbalances, the occurrence of voltage fluctuations, the possibility of bidirectional power circulation in the user's power supply network. During the hours of maximum production of renewable sources, it is possible to result in changes in power flows in the network, as well as changes in the values and direction of electrical currents in the event of a fault.

Generally these sources are connected to public electricity through inverters that allow control over two output parameters: active power and reactive power[6],[7]. When PV sources generate active power, they can alter the voltage profile within the grid. Consuming reactive power can lower the voltage with minimal effect on active power output, making this the preferred approach. Reducing active power can help mitigate overvoltages in the network, but it also decreases the total energy produced by the system and is typically applied only when voltages are very high and reactive power control alone cannot resolve the issue.

The reverse circulation of power in the circuit with renewable sources operating in capacitive mode can lead to an increase in the magnetizing electric current of the transformer and to a change in its characteristics [2], [3].

Additionally, changes in the transformer's magnetization characteristics can generate harmonics in the electric current, leading to increased losses in the power supply network. Limiting the energy fed into the public grid for operational reasons is generally unacceptable to investors, who aim to maximize the energy delivered. Equipping local renewable sources with energy storage systems allows excess energy to be absorbed and helps reduce reverse power flow conditions.
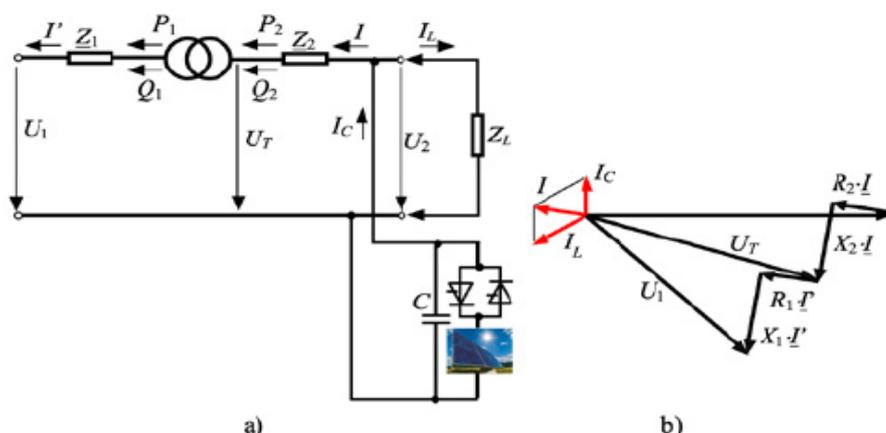
Fig.3. Reverse power flow in circuits with renewable sources
a) schematic diagram; b) phasor diagram

3. THE EFFECT OF REVERSE POWER FLOW IN MODERN ELECTRICAL NETWORKS

Reverse circulation appears when the electricity produced locally—usually by distributed renewable sources—surpasses the consumption of nearby users. In this situation, the excess energy flows backward toward the transmission grid or other points in the distribution network. In other words, the power starts moving "upstream," contrary to the grid's original design, which anticipated electricity flowing in only one direction, from centralized power plants to consumers. [5],[8]

The impact of the reverse circulation effect is particularly important in modern electrical networks, where these phenomena can lead to:

-power quality issues, they can generate fluctuations in voltage and frequency, affecting the stable operation of the electrical system.

-increased risk to equipment and user safety, such situations may create operating conditions that were not considered in the original network design.

-challenges in load balancing, managing rapidly changing energy flows becomes more difficult, especially when renewable generation cannot be accurately predicted.

-interference with network and protection system operation, when energy begins to flow opposite to the usual direction, the protection schemes may no longer function as intended, leading to possible malfunctions.

-overloading of network components, reverse power flows may overtake the designed capacity of transmission lines and transformers [9], [10].

3.1. Technical effects

-Voltage and frequency instability:
• feeding surplus energy back into the main grid can disrupt the system's operating conditions, leading to:
• rapid voltage rises at nearby nodes.

• frequency variations that may interfere with the functioning of sensitive devices.
    -Harmonics and power quality concerns:
• distributed generation units, particularly PV inverters, can inject harmonic distortions into the grid, negatively influencing.
• the overall stability of the power system, and the proper functioning of devices connected to the network.[13]
    -Issues with protection relays:
• traditional protection relays are configured to identify faults assuming power flows only in one direction. When the flow reverses, they may incorrectly interpret it as a fault, potentially triggering unwarranted disconnections.
    -Overloading of equipment.
    Transformers and power lines are built for power to move in a single direction, when the flow reverses, it can lead to:
• increased energy losses caused by the Joule effect [1], [8], [12], [14]
• excessive heating, faster deterioration of insulation, and a shorter operational lifetime of the equipment.

3.2. Economic effects

Billing challenges
• without bidirectional metering, accurately accounting for energy exchanged with the grid becomes difficult, potentially causing revenue losses for network operators.
    - Decreased energy efficiency
• overloaded transmission lines and transformers lead to higher energy losses.
• excessively stressed equipment must be replaced more often, which raises maintenance expenses.
    - Need for additional investments
• upgrading the grid to accommodate two-way power flows requires significant financial resources.

3.3. Operational effects

    - Higher risk of outages:
• uncontrolled bidirectional flows can lead to failures within the local network or at consumer installations. [14]
    - Increased operational complexity, managing power flows in both directions demands:
• continuous real-time monitoring.
• the use of advanced optimization algorithms.

4. CONCLUSSIONS

The continued growth of the number of energy sources connected to an operator's network—and the corresponding rise in locally generated power—can

introduce new power flow patterns that must be identified and managed under various operating conditions.

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EVALUATION OF ELECTROMAGNETIC FIELD EXPOSURE IN MODERN RESIDENTIAL BUILDINGS

OANA CARAŞCA[1]

Abstract: The rapid development of electrical, electronic and wireless technologies in residential buildings has led to an increased presence of electromagnetic fields (EMF) in indoor environments. Electrical installations, household appliances, wireless communication systems and building automation generate electromagnetic fields with different frequencies and intensities. This paper analyzes the main indoor EMF sources, the types of electromagnetic fields encountered in buildings, assessment methods, regulatory limits and technical solutions for exposure reduction. A case study based on in-situ measurements in a residential building is also presented.

Key words: electromagnetic fields, residential buildings, EMF exposure, indoor environment, civil engineering.

1. INTRODUCTION

Modern residential buildings integrate an increasing number of electrical and electronic systems intended to improve comfort, safety and energy efficiency. As a consequence, occupants are continuously exposed to electromagnetic fields (EMF) generated by power supply systems, household appliances, information technology equipment and wireless communication devices [1].

From the perspective of civil engineering, indoor environmental quality has become a key design criterion, alongside thermal comfort, acoustic performance and indoor air quality. Electromagnetic exposure is now considered an additional factor influencing occupants' well-being and long-term health [2].

2. SOURCES OF ELECTROMAGNETIC FIELDS IN BUILDINGS

Electromagnetic fields in residential buildings originate from a wide range of sources operating at different frequencies. Low-frequency fields are mainly produced by electrical power systems, while higher frequencies are associated with wireless communication technologies.

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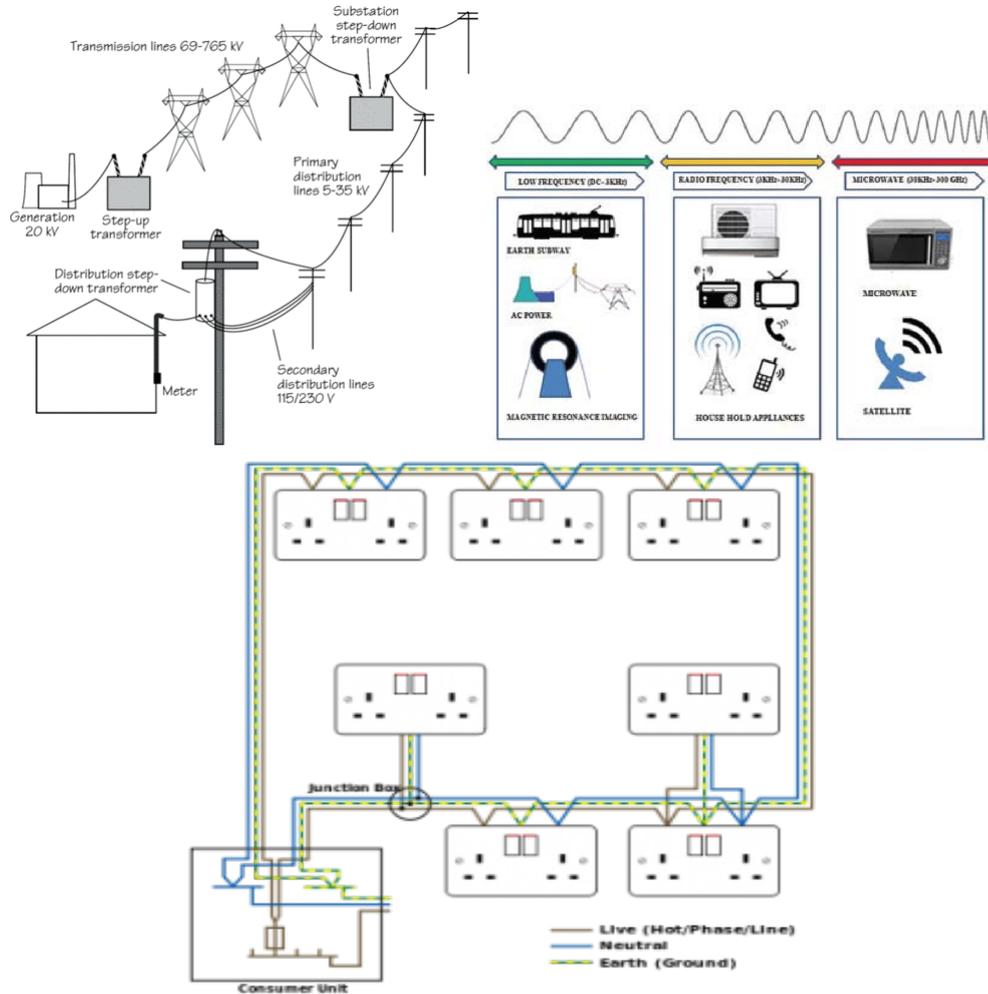
Fig.1. Typical indoor sources of electromagnetic fields in a residential building

As shown in Fig. 1, The most common indoor EMF sources include electrical power supply networks operating at 50 Hz, electrical distribution boards, household appliances, IT equipment, wireless communication systems and building automation installations [3]. The cumulative effect of these sources leads to a complex electromagnetic environment that varies spatially and temporally.

3. TYPES OF ELECTROMAGNETIC FIELDS

3.1. Extremely Low Frequency Fields (ELF)

Extremely low frequency electromagnetic fields are generated by alternating current electrical installations and devices connected to the power grid. These fields are characterized by frequencies up to 300 Hz and are mainly associated with electric and magnetic components around cables and equipment [4].

3.2. Radiofrequency Fields (RF)

Radiofrequency electromagnetic fields are produced by wireless communication systems and electronic devices. In residential buildings, RF fields typically range from several hundred MHz to a few GHz and propagate through indoor spaces, interacting with building materials.
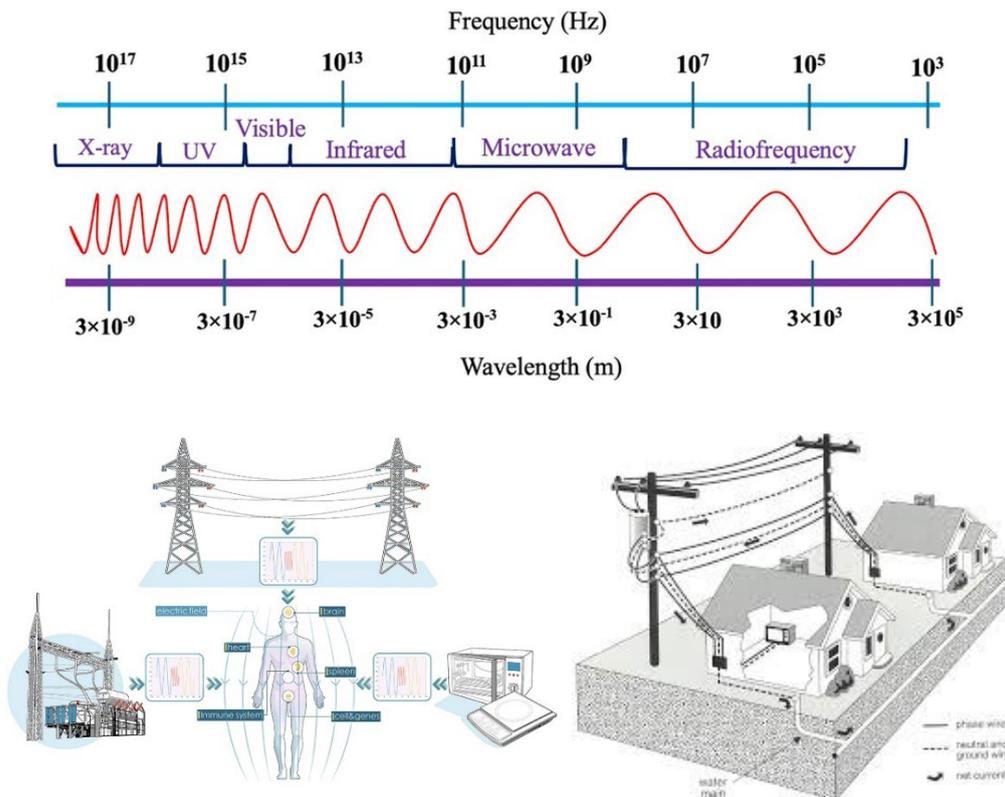
Fig.2. Classification of electromagnetic fields encountered in residential buildings according to frequency

4. METHODS FOR EMF EXPOSURE ASSESSMENT

4.1. Direct Measurements

Direct measurement represents the most reliable method for assessing actual EMF exposure levels. Specialized equipment such as electromagnetic field analyzers, electric and magnetic field probes, and broadband or frequency-selective instruments are used [6].

Measurements are usually performed in frequently occupied areas such as living rooms, bedrooms and home offices, at representative heights corresponding to occupant presence.

Measurements were performed in representative indoor locations, such as living rooms and bedrooms, at typical occupant height (Fig. 3).
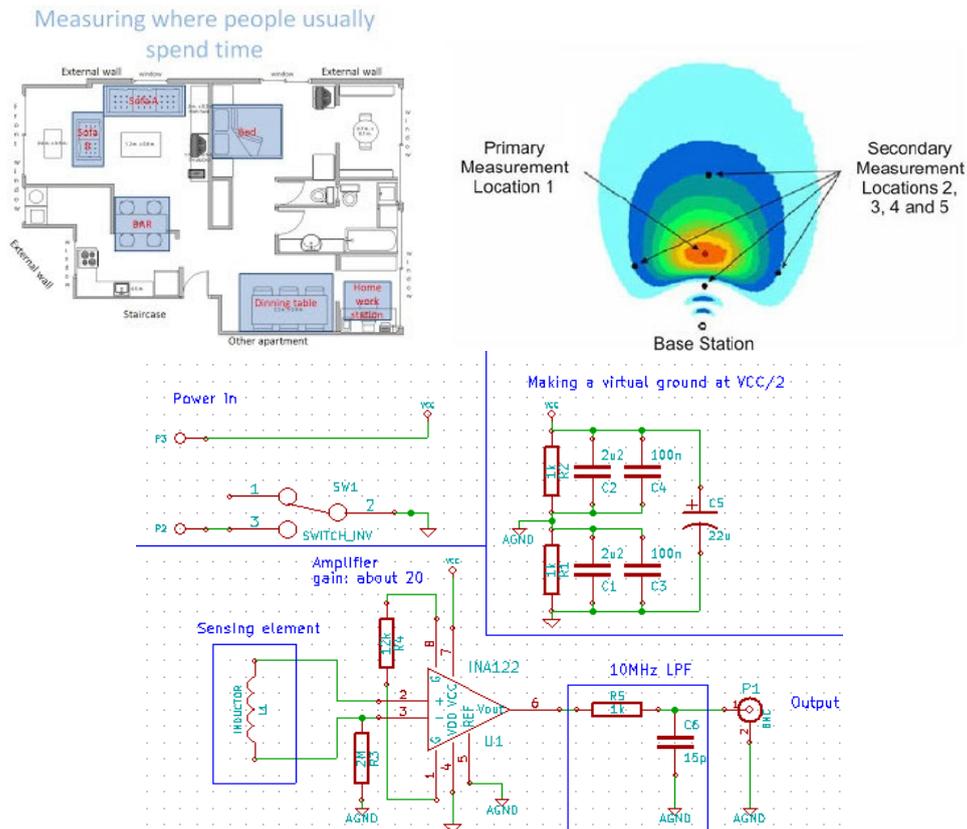
Fig.3. Typical measurement points for electromagnetic field assessment in residential rooms

4.2. Numerical Modelling and Simulation

In modern building design, electromagnetic field distribution can be assessed through numerical modelling and simulation. Specialized software allows the analysis of EMF propagation depending on building geometry, source location and material properties [7]. This approach is particularly useful during the design stage.

5. REGULATORY FRAMEWORK AND EXPOSURE LIMITS

Exposure to electromagnetic fields is regulated internationally by the guidelines issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). These guidelines establish reference levels for general public exposure and occupational exposure [8]. At European and national levels, these recommendations are implemented through specific directives and standards related to electromagnetic compatibility and public health protection [9].

6. MEASURES FOR REDUCING EMF EXPOSURE

Several technical and design measures can be applied to reduce EMF exposure in residential buildings, including proper positioning of electrical and electronic equipment, use of shielded cables, adequate grounding of electrical installations, limitation of prolonged exposure to wireless devices and application of construction materials with electromagnetic attenuation properties [10].

7. CASE STUDY: EMF ASSESSMENT IN A RESIDENTIAL BUILDING

7.1. Building Description

The case study was conducted in a multi-storey residential building equipped with standard electrical installations, Wi-Fi networks and typical household appliances. Measurements were performed in living rooms and bedrooms, at a height of approximately 1.2 m above floor level.

7.2. Measurement Results and Analysis

Measured electric field values for ELF sources ranged between 5 and 40 V/m in the vicinity of electrical panels, while RF field levels measured near Wi-Fi routers remained below 3 V/m. All recorded values were below the ICNIRP reference levels for public exposure. The spatial distribution of electromagnetic field intensity highlights higher values in the proximity of electrical panels and wireless routers (Fig. 4).

7.3. Discussion

The spatial distribution of electromagnetic fields highlights localized increases in proximity to electrical panels and wireless routers.

However, normal operating conditions ensure compliance with applicable exposure limits, emphasizing the importance of proper equipment placement and design optimization.

8. CONCLUSIONS

Electromagnetic fields are an unavoidable component of modern residential buildings. Through proper assessment, compliance with regulations and implementation of technical mitigation measures, EMF exposure can be maintained at safe levels.

Integrating electromagnetic field evaluation into the design and operation of residential buildings contributes to healthier indoor environments and supports sustainable construction principles.
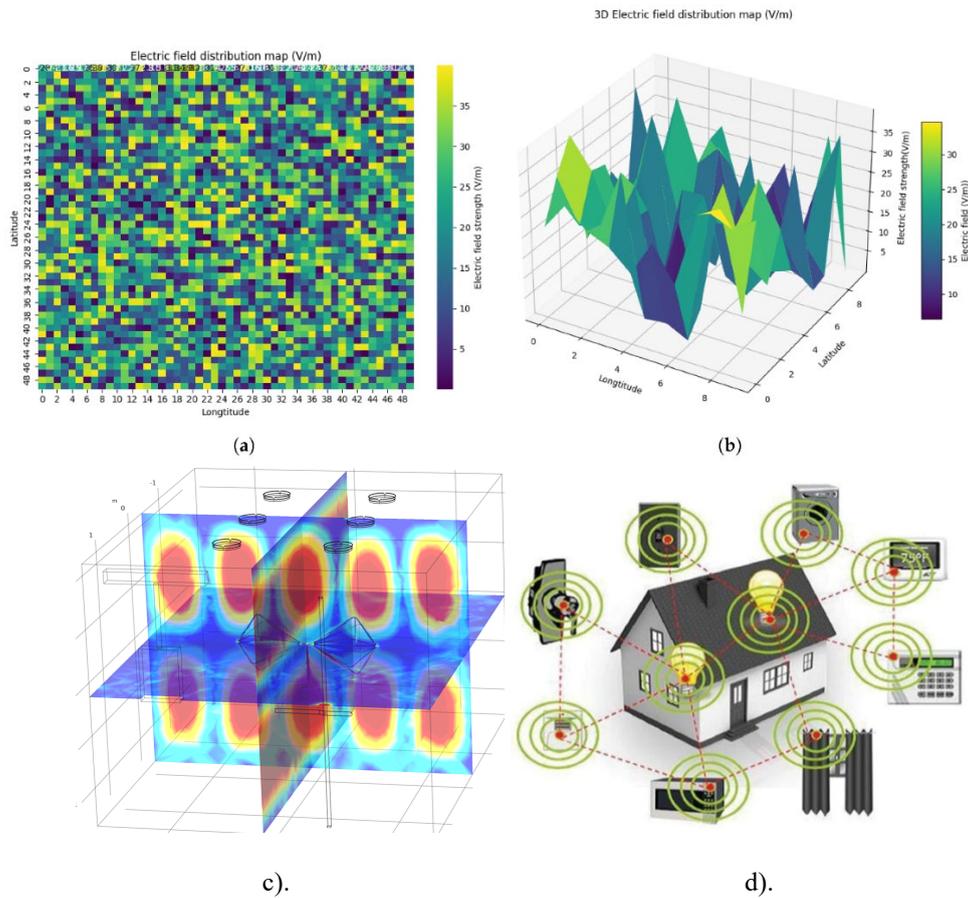
Fig.4. Electromagnetic field intensity distribution in a living room – case study

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ON-LINE ESTIMATION OF THE CORE LOSS RESISTANCE AND THE EDDY-CURRENT-ASSOCIATED LEAKAGE INDUCTANCE IN THE PARALLEL MODEL OF THE INDUCTION MOTOR

OLIMPIU STOICUȚA[1], VALI – CHIVUȚA SÎRB[2], NADIA STOICUȚA[3]

Abstract: This article presents a new online method for estimating the core-loss resistance and the leakage inductance associated with eddy currents in the parallel model of the induction motor. The proposed method uses information regarding the stator current, stator voltage, and motor rotational speed to identify additional parameters of the equivalent circuit, contributing to a more accurate description of the machine's electromagnetic behavior. The performance of the estimator is evaluated through numerical simulation performed in the Matlab-Simulink environment.

Key words: induction machines, simulation, core-loss resistance, leakage inductance.

1. INTRODUCTION

Induction motors represent the backbone of modern industrial systems due to their robustness, efficiency, and low manufacturing cost. Achieving high-performance operation of these machines, especially within vector-control frameworks, requires an accurate mathematical representation of their electrical and magnetic behavior. This accuracy critically depends on the precise knowledge of the motor's electrical parameters [2], [6], [7], [10].

While classical induction motor models typically neglect iron losses, numerous studies have demonstrated that these losses significantly influence both transient and steady-state behavior, especially when the motor is supplied by voltage-source inverters operating at high switching frequencies [4], [5]. To address this limitation, the parallel model of the induction motor includes a dedicated core-loss branch consisting of two key parameters: the core-loss resistance (R_f), representing hysteresis and resistive eddy-current losses, and the eddy-current–associated leakage inductance (L_f), modeling the dynamic behavior of eddy currents in the stator core [3], [4], [5].

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Accurate identification or estimation of R_f and L_f is essential for improving the fidelity of the mathematical model, for enhancing the accuracy of flux observers, and for achieving superior dynamic performance in vector control systems. However, these parameters are highly dependent on excitation frequency, magnetic saturation, and temperature, making their estimation nontrivial. Despite their importance, only a limited number of studies have proposed practical and reliable estimation procedures for the parameters of the iron-loss branch in the parallel model.

Given this context, this article proposes an on-line estimation method for determining the core-loss resistance R_f and the eddy-current-associated leakage inductance L_f of the induction motor.

2. THE MATHEMATICAL MODELS OF THE INDUCTION MOTOR

The equations that define the parallel mathematical model of the induction motor, written based on the equivalent circuit (see Fig. 1), in a stator reference frame, are presented below [9].
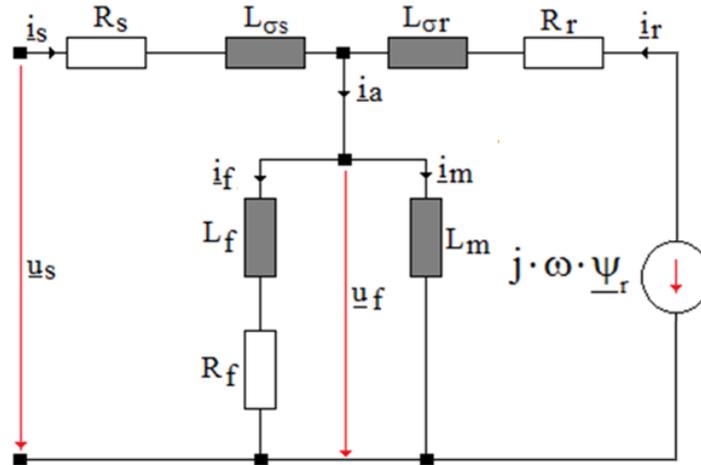
Fig.1. The equivalent circuit of the induction motor

- the stator-voltages equation

$$\underline{u}_s = R_s \cdot \underline{i}_s + \frac{d}{dt}\underline{\psi}_s \tag{1}$$

- the rotor-voltages equation

$$0 = R_r \cdot \underline{i}_r + \frac{d}{dt}\underline{\psi}_r - j \cdot \omega \cdot \underline{\psi}_r \tag{2}$$

- the stator flux equation

$$\underline{\psi}_s = \underline{\psi}_m + L_{\sigma s} \cdot \underline{i}_s \tag{3}$$

- the rotor flux equation

$$\underline{\psi}_r = \underline{\psi}_m + L_{\sigma r} \cdot \underline{i}_r \tag{4}$$

- the air-gap flux equation

$$\underline{\psi}_m = L_m \cdot \underline{i}_m \tag{5}$$

- the current equation

$$\underline{i}_s + \underline{i}_r = \underline{i}_m + \underline{i}_f \tag{6}$$

- magnetic branch voltage equation

$$\underline{u}_f = R_f \cdot \underline{i}_f + L_f \cdot \frac{d}{dt}\underline{i}_f = \frac{d}{dt}\underline{\psi}_m \tag{7}$$

- the motion equation of the induction motor

$$J \cdot \frac{d}{dt}\omega_r = T_e - F \cdot \omega_r - T_L \tag{8}$$

where T_e is the electromagnetic torque and T_L is the load torque

$$T_e = \frac{3}{2} \cdot \frac{z_p}{L_{\sigma r}} \cdot \mathrm{Im}\left(\underline{\psi}_r^* \cdot \underline{\psi}_m\right) \tag{9}$$

The following notations were used in the above relationships:

$\underline{u}_s = u_{ds} + j \cdot u_{qs}$; $\underline{u}_f = u_{df} + j \cdot u_{qf}$; $\underline{i}_s = i_{ds} + j \cdot i_{qs}$; $\underline{i}_r = i_{dr} + j \cdot i_{qr}$; $\underline{i}_m = i_{dm} + j \cdot i_{qm}$;

$\underline{i}_f = i_{df} + j \cdot i_{qf}$; $\underline{\psi}_s = \psi_{ds} + j \cdot \psi_{qs}$; $\underline{\psi}_r = \psi_{dr} + j \cdot \psi_{qr}$; $\underline{\psi}_r^* = \psi_{dr} - j \cdot \psi_{qr}$;

$\underline{\psi}_m = \psi_{dm} + j \cdot \psi_{qm}$; $j = \sqrt{-1}$; $\omega = z_p \cdot \omega_r$; $L_r = L_{\sigma r} + L_m$; $L_s = L_{\sigma s} + L_m$.

3. ON-LINE ESTIMATION OF R_f AND L_f PARAMETERS

The method for estimating the parameters R_f and L_f is based on relation (7). Relation (7) can be written as follows

$$\begin{bmatrix} u_{df} \\ u_{qf} \end{bmatrix} = A \cdot \begin{bmatrix} R_f \\ L_f \end{bmatrix} \tag{10}$$

where: $A = \begin{bmatrix} i_{df} & \dfrac{d}{dt} i_{df} \\ i_{qf} & \dfrac{d}{dt} i_{qf} \end{bmatrix}$.

Using the least-squares method, we can extract the parameters R_f and L_f (the system solution), as follows

$$\begin{bmatrix} \hat{R}_f \\ \hat{L}_f \end{bmatrix} = \left(B^T \cdot B \right)^{-1} \cdot B^T \cdot \begin{bmatrix} \hat{u}_{df} \\ \hat{u}_{qf} \end{bmatrix} \tag{11}$$

where: $B = \begin{bmatrix} \hat{i}_{df} & \dfrac{d}{dt} \hat{i}_{df} \\ \hat{i}_{qf} & \dfrac{d}{dt} \hat{i}_{qf} \end{bmatrix}$; $\hat{i}_{df}$, $\hat{i}_{qf}$, $\hat{u}_{df}$ and $\hat{u}_{qf}$ are the iron loss currents and iron branch voltages estimated.

Considering relations (1), (3), and (7), the following expression can be written:

$$\underline{u}_f = \underline{u}_s - R_s \cdot \underline{i}_s - L_{\sigma s} \cdot \frac{d}{dt} \underline{i}_s \tag{12}$$

Under these conditions, $\hat{u}_{df}$ and $\hat{u}_{qf}$ can be estimated as follows

$$\begin{bmatrix} \hat{u}_{df} \\ \hat{u}_{qf} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -R_s & 0 & -L_{\sigma s} & 0 \\ 0 & 1 & 0 & -R_s & 0 & -L_{\sigma s} \end{bmatrix} \cdot \begin{bmatrix} u_{ds} \\ u_{qs} \\ i_{ds} \\ i_{qs} \\ \dfrac{d}{dt} i_{ds} \\ \dfrac{d}{dt} i_{qs} \end{bmatrix} \tag{13}$$

where u_{ds} and u_{qs}, respectively i_{ds} and i_{qs}, are the stator voltages and currents in the d-q reference frame, obtained by applying the Clarke transformation to the voltages and currents measured, using the voltage and current transducers.

On the other hand, taking into account relations (6), (5) and (4) we can write the following expression:

$$\underline{i}_f = \underline{i}_s + \frac{1}{L_{\sigma r}} \cdot \underline{\psi}_r - \left(\frac{1}{L_{\sigma r}} + \frac{1}{L_m} \right) \cdot \underline{\psi}_m \tag{14}$$

Under these conditions, $\hat{i}_{df}$ and $\hat{i}_{qf}$ can be estimated as follows

$$
\begin{bmatrix} \hat{i}_{df} \\ \hat{i}_{qf} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \dfrac{1}{L_{\sigma r}} & 0 & -\left(\dfrac{1}{L_{\sigma r}}+\dfrac{1}{L_m}\right) & 0 \\ 0 & 1 & 0 & \dfrac{1}{L_{\sigma r}} & 0 & -\left(\dfrac{1}{L_{\sigma r}}+\dfrac{1}{L_m}\right) \end{bmatrix} \cdot \begin{bmatrix} i_{ds} \\ i_{qs} \\ \hat{\psi}_{dr} \\ \hat{\psi}_{qr} \\ \hat{\psi}_{dm} \\ \hat{\psi}_{qm} \end{bmatrix} \tag{15}
$$

where i_{ds} and i_{qs}, are the stator currents in the d-q reference frame, obtained by applying the Clarke transformation to the currents measured, using the current transducers.

In relation (15), $\hat{\psi}_{dr}$, $\hat{\psi}_{qr}$, and respectively $\hat{\psi}_{dm}$ and $\hat{\psi}_{qm}$ are the d–q components of the estimated rotor flux and of the estimated magnetizing flux.

In order to estimate the magnetization flux, relations (1) and (3) are used. Thus, the relations that define this estimator are

$$
\underline{\hat{\psi}}_m = \underline{\hat{\psi}}_s - L_{\sigma s} \cdot \underline{i}_s \tag{16}
$$

where $\underline{\hat{\psi}}_s = \int_0^t \left(\underline{u}_s - R_s \cdot \underline{i}_s\right) d\tau$.

Relation (16) can also be written in the following form

$$
\begin{bmatrix} \hat{\psi}_{dm} \\ \hat{\psi}_{qm} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -L_{\sigma s} & 0 \\ 0 & 1 & 0 & -L_{\sigma s} \end{bmatrix} \cdot \begin{bmatrix} \hat{\psi}_{ds} \\ \hat{\psi}_{qs} \\ i_{ds} \\ i_{qs} \end{bmatrix} \tag{17}
$$

where: $\hat{\psi}_{ds} = \int_0^t \left(u_{ds} - R_s \cdot i_{ds}\right) d\tau$; $\hat{\psi}_{qs} = \int_0^t \left(u_{qs} - R_s \cdot i_{qs}\right) d\tau$.

On the other hand, taking into account relations (2) and (4) the estimator related to the rotor flux is defined by the following expression.

$$
\frac{d}{dt}\underline{\hat{\psi}}_r = \left(-\frac{R_r}{L_{\sigma r}} + j \cdot z_p \cdot \omega_r\right) \cdot \underline{\hat{\psi}}_r + \frac{R_r}{L_{\sigma r}} \cdot \underline{\hat{\psi}}_m \tag{18}
$$

Relation (18) can also be written in the following form

$$
\begin{bmatrix} \hat{\dot{\psi}}_{dr} \\ \hat{\dot{\psi}}_{qr} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_r}{L_{\sigma r}} & -z_p \cdot \omega_r \\ z_p \cdot \omega_r & -\dfrac{R_r}{L_{\sigma r}} \end{bmatrix} \cdot \begin{bmatrix} \hat{\psi}_{dr} \\ \hat{\psi}_{qr} \end{bmatrix} + \dfrac{R_r}{L_{\sigma r}} \cdot \begin{bmatrix} \hat{\psi}_{dm} \\ \hat{\psi}_{qm} \end{bmatrix} \tag{19}
$$

The on-line estimation method presented above is summarized in the following block diagram (see Fig.2).

In Fig. 2, **IM** denotes the induction motor, $\mathbf{T_\omega}$ denotes the speed transducer, and **TS** (system transformations) denotes the Clarke transformer block.
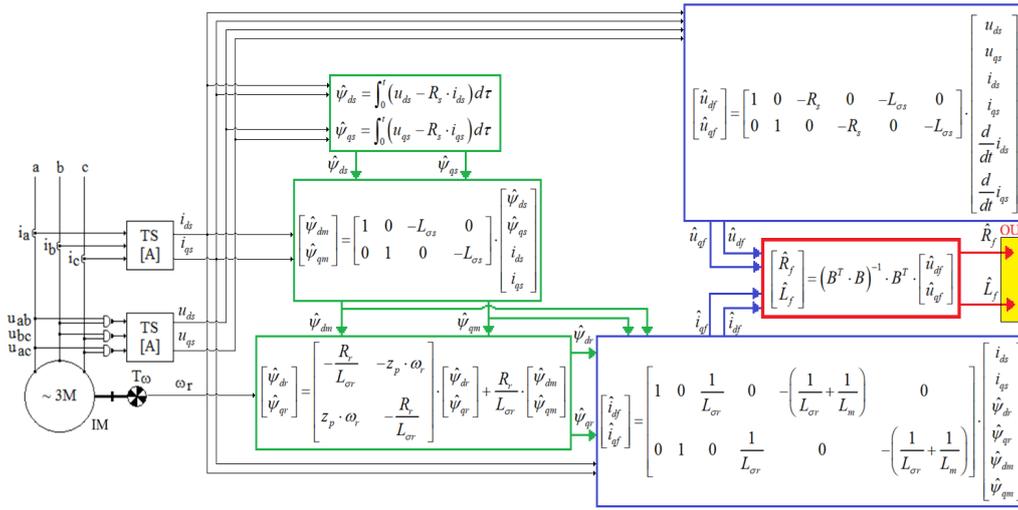
Fig.2. Block diagram of the R_f and L_f on-line estimation method

From the above, it can be seen that the on-line estimation method for R_f and L_f is based on three flux observers (stator flux observer, air-gap flux observer and rotor flux observer).

4. SIMULATIONS RESULTS

To test the previously presented online estimator, a 1.5 [kW] induction motor is used, which has the electrical and mechanical parameters presented in Table 1.

The estimator is tested via simulation in the Matlab-Simulink environment, in the case of direct on-load (DOL) starting of the induction motor. The induction motor is started under load, with a torque equal to its rated value.

Both the induction motor and the estimator presented previously are simulated in continuous time in Matlab-Simulink.

In the simulation test, the ode15s (stiff/NDF) integration method is used, with a relative and absolute error of 10^{-12}. The final simulation time is t_f=1 [s].

In the case of the simulation test, the induction motor is supplied with three-phase voltages at a frequency of 50 [Hz].

Table 1. **The electrical and mechanical parameters of the induction motor [1]**

	Name	Value		Name	Value
R_s	Stator resistance	4.85 [Ω]	J	Motor inertia	0.031[kg·m²]
R_r	Rotor resistance	3.805 [Ω]	F	Friction coefficient	0.008[N·m·s/rad]
R_f	Core loss resistance	500 [Ω]	n_N	Rated speed	1420 [rpm]
L_s	Stator inductance	0.274 [H]	z_p	Number of pole pairs	2
L_r	Rotor inductance	0.274 [H]	f_N	Rated frequency	50 [Hz]
L_m	Mutual inductance	0.258 [H]	U_N	Rated voltage	220 Δ/380 Y [V]
L_f	Eddy currents leakage inductance	0.1 [H]	M_N	Rated torque	10 [N·m]

The simulation model of the induction motor – R_fL_f estimator assembly, is presented in Fig. 3.
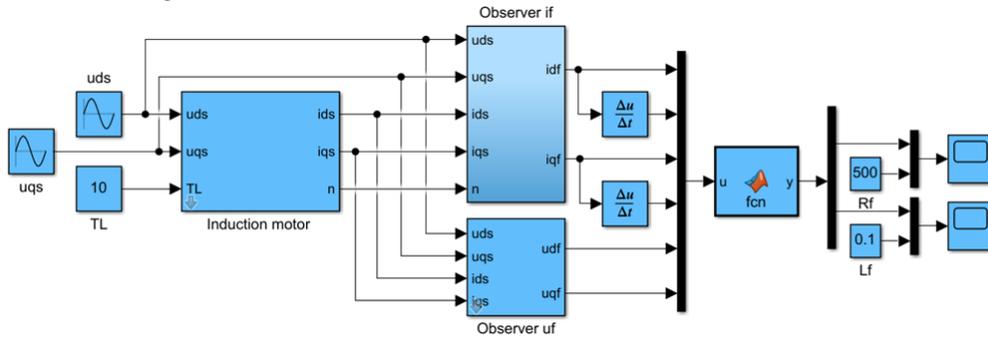
Fig.3. Matlab-Simulink simulation model of the R_fL_f estimator

In the simulation program in Fig.3, the induction motor is simulated in continuous time, using an S-Function block [8], [9].

The internal structure of the block used in estimating the u_{df} – u_{qf} stresses is shown in Fig. 4.
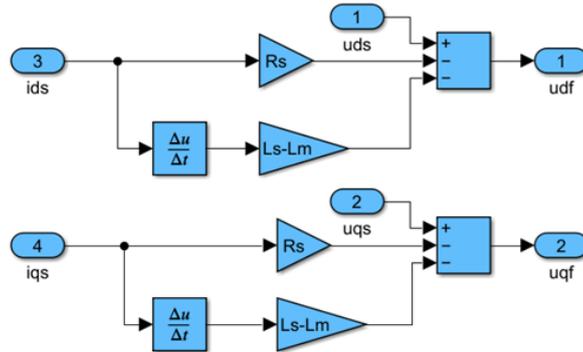
Fig.4. The internal structure of the block used in u_{df} – u_{qf} estimating

On the other hand, the internal structure of the block used in estimating the d-q components of the current $\underline{i}_f$, is presented in Fig.5.
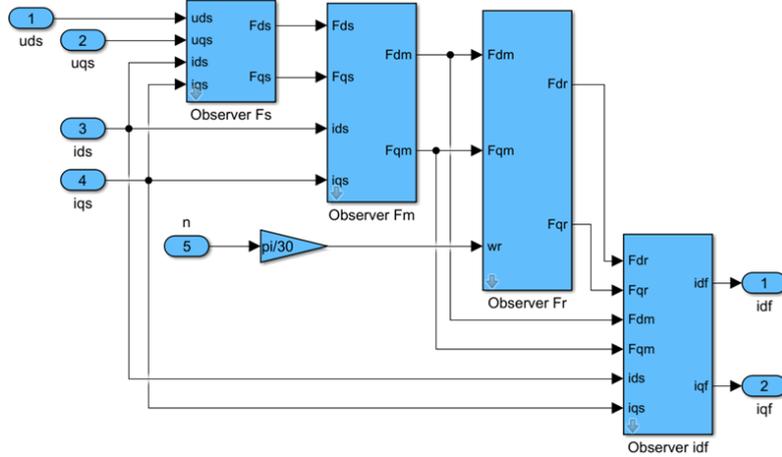
Fig.5. The internal structure of the block used in $i_{df} – i_{qf}$ estimating

The Matlab function used in estimating R_f and L_f, taking into account relation (11), is presented in Fig.6.

```
function y = fcn(u)
Ba=[u(1) u(2);
    u(3) u(4)];
Ua=[u(5);u(6)];
y = (inv(Ba'*Ba))*(Ba')*Ua;
```

Fig.6. The Matlab function used in estimating Rf and Lf

After running the program in Fig.3, under the previously presented conditions, the following results are obtained (see Fig. 7 and Fig. 8).
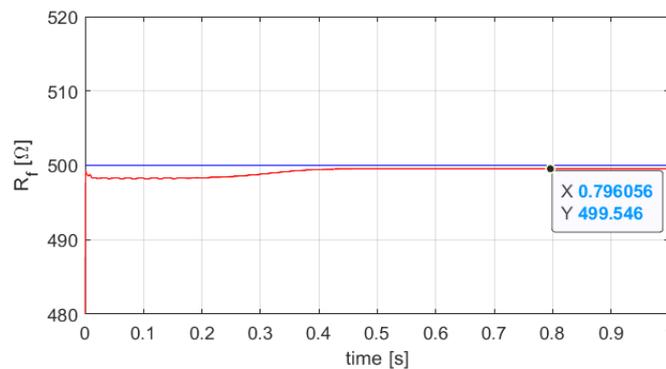
Fig.7. The variation over time of the estimated R_f resistance, together with the reference value.
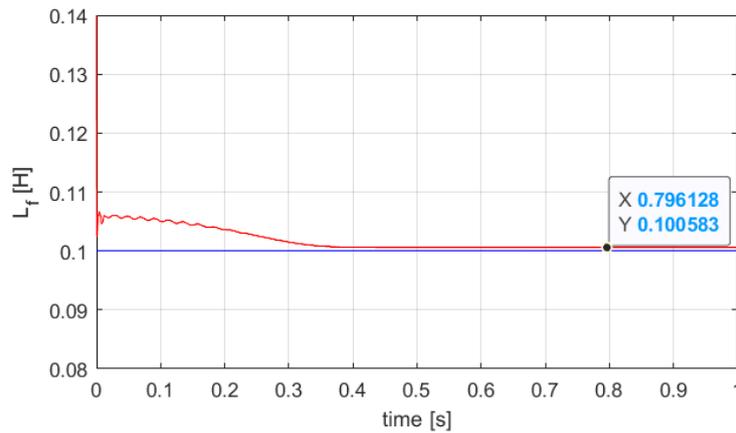
Fig.8. The variation over time of the estimated L_f inductance, together with the reference value.

From the previous figures, it can be observed that the on-line estimation method converges to the reference values in approximately 0.4 [s] (identical to the starting time motor), for the case in which the three-phase supply voltages have a frequency of 50 [Hz].

From Fig. 7, it can be observed that the steady-state error in the on-line estimation of the resistance R_f is approximately 0.45 [Ω].

On the other hand, from Fig. 8, it can be observed that the steady-state error in the estimated inductance L_f is approximately $5.8 \cdot 10^{-4}$ [H].

5. CONCLUSIONS

The article presents a new method for the online estimation of the core-loss resistance R_f and the eddy-current-associated leakage inductance L_f of an induction motor. Simulation results confirm that the proposed online estimation method for R_f and L_f is both accurate and robust, demonstrating its potential for practical implementation in industrial and research applications.

The detailed mathematical formulations of the proposed estimators, together with the results obtained from the Matlab-Simulink simulations, offer substantial support for researchers and practitioners working with induction motors.

A promising direction for future work is the practical implementation of the proposed estimator.

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INTEGRATED APPROACHES TO THE ASSESSMENT OF RISK SCENARIOS TO THE NATIONAL POWER SYSTEM

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Abstract: Ensuring the resilience and reliability of the National Power System (NPS) has become a strategic priority for modern states, given the critical role that electricity infrastructure plays in national security, economic stability, and societal well-being. The increasing complexity of the NPS, combined with emerging threats such as system malfunctions, cyber intrusions, and intentional harmful actions, requires comprehensive and integrated risk-assessment methodologies. This paper examines multi-layered approaches to evaluating risk scenarios that threaten the functioning of the NPS, with a specific focus on operational insecurity and the potential for terrorist-related disruptions. By synthesizing insights from systems engineering, critical infrastructure protection, and risk analysis, the study presents a framework that integrates technical, organizational, and environmental factors into a unified risk-assessment model. The findings highlight the need for cross-sector coordination, advanced monitoring tools, and adaptive response strategies to strengthen the resilience of national power infrastructures. Ultimately, this research contributes to developing more robust methods for anticipating, evaluating, and mitigating high-impact risks to the power system.

Keywords: assessment, risk scenarios, National Power System.

1. INTRODUCTION

The National Power System (NPS) represents one of the most essential components of a country's critical infrastructure. Its uninterrupted operation underpins nearly all sectors of modern life, from healthcare and industry to transport and communication [27], [29], [35]. As energy demand grows and power networks expand in technological complexity, the NPS faces increasing vulnerability to a wide array of risk factors. These include technical failures, natural hazards, cyber threats, and

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intentional disruptive actions. Consequently, the assessment and management of risks to the NPS have become central issues in national resilience planning [11], [14], [16].

Among the most significant concerns are insecurity in the functioning of the NPS – such as cascading failures, equipment malfunctions, and operational instability – and the heightened possibility of terrorist attacks targeting power generation, transmission, or control infrastructure. While attacks on energy systems are relatively rare, their potential consequences are severe, including widespread blackouts, economic disruption, and threats to public safety [28], [33], [34]. Therefore, understanding these risks requires more than traditional single-factor models; it necessitates an integrated approach that considers technical systems, human factors, interdependencies, and emerging threat landscapes [8], [12], [15], [19].

Integrated risk-assessment methodologies combine multiple analytical perspectives – engineering analysis, probabilistic risk assessment, scenario modelling, and organizational resilience frameworks – to capture the complexity of threats facing the NPS [24], [26]. Such holistic methods enable stakeholders to identify vulnerabilities, evaluate the likelihood and impact of different scenarios, and prioritize mitigation measures across physical, digital, and organizational domains.

This paper explores these integrated approaches in depth, focusing on how they can be applied to assess two critical categories of risk: (1) insecurity in the functioning of the NPS and (2) potential terrorist actions against the system. Through this analysis, the study aims to contribute to the ongoing efforts to ensure the security, stability, and resilience of national power systems in an increasingly uncertain environment. [1], [3], [18].

The NPS functions as an interconnected system to the European Power System – ENTSO-E, which represents the European Network of Transmission System Operators for Electricity [2], [10], [13].

Romania, through the national electricity transmission company, Transelectrica, which is a national transmission and system operator (TSO), has an active and essential role within ENTSO-E, being a full member [17], [20], [23]. It manages and operates the electricity transmission system, ensuring electricity exchanges between Romania and the countries of the European Union and the neighbouring countries that are not part of the European Union (Serbia, Ukraine and the Republic of Moldova) [30], [32].

The NPS, through the Electricity Power Transmission Grid, is composed of the following critical energy infrastructures, fig.1:
- 82 power substations, of which:
    - 1 power substation in a gauge of 750 kV, but functioning at 400 kV;
    - 38 power substations of 400 kV;
    - 43 power substations of 220 kV.
- 8834.4 km overhead power lines, of which:
    - 3.1 km – 750 kV;
    - 4915.2 km – 400 kV;
    - 3875.6 km – 220 kV;
    - 40.4 km – 110 kV (interconnection Serbia, Ukraine and the Republic of Moldova).

- 216 transformation units totaling 38 058 MVA.
- 1 National Energy Dispatch – NED;
- 5 Territorial Dispatchers – TED [21], [25], [31].
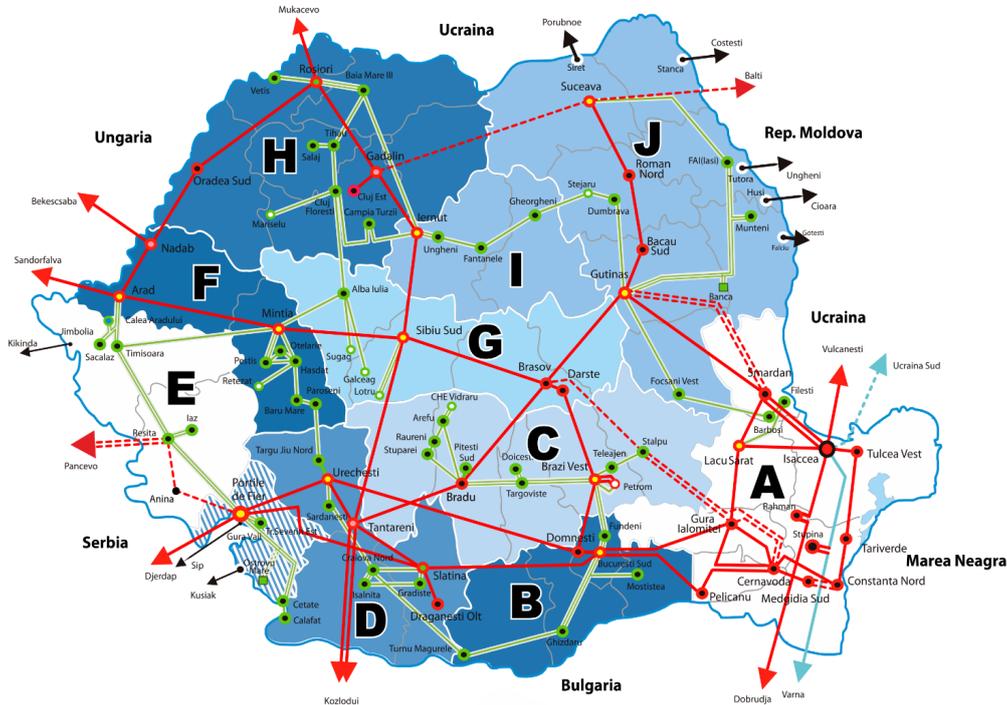
Fig.1. National Power System map (source: Transelectrica)

2. ASSESSMENT OF RISK SCENARIOS

2.1. Insecurity in functioning of the NPS

The identification, assessment and manifestation are shown in Table 1 [4], [5], [6]

Table 1. **Insecurity in functioning of the NPS**

Risk scenario: INSECURITY IN FUNCTIONING OF THE NPS				
1	Local technical incidents	Likelihood	3 Medium	• Equipment triggers take place and some equipment becomes unavailable for a very long period of time; • The risk of overloads on important lines and transformation units, including interconnection lines, increases and then cascading faults occur; • A separation of the system
		Gravity/ Impact	3 Medium	
		Risk level	9	
		Scenario type	7 – 12 Moderate	

2			may occur and certain areas may function in island mode; • Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants. This causes the limitation or total loss of reserves; • Major deviations of the NPS functioning parameters are recorded; • The N-1 safety criterion is no longer met; • Also, the low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS; • There is a major risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
2	Multiple technical incidents caused by extreme weather conditions	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>3 Medium</td></tr><tr><td>Risk level</td><td>9</td></tr><tr><td>Scenario type</td><td>7 – 12 Moderate</td></tr></table>	• Extreme weather leads to accidental failure of several equipment (possibly of the same construction type) in a very short time; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of equipment; • Difficulties may arise in carrying out faults remediation work in substations, caused by the large number of equipment of the same type affected and the lack of equipment in security stocks; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying some grid areas for a very

			• long period, correlated with the time required to repair/replace destroyed/damaged assets; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
3	Simultaneous technical incidents	Likelihood: **3 Medium** Gravity/ Impact: **4 High** Risk level: 12 Scenario type: **7 – 12 Moderate**	• Separation of a grid area may occur where there are not enough production units to ensure consumption of the area; • Deviations of functioning parameters outside the permissible limits shall occur; • The N-1 safety criterion is no longer met; • Difficulties may arise in carrying out faults remediation work in substations, caused by the large number of equipment of the same type affected and the lack of equipment in security stocks; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged assets; • Congestions can occur on interconnection lines and even the impossibility of securing electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
4	Complexity of control mechanisms of power systems	Likelihood: **2 Low** Gravity/ Impact: **4 High** Risk level: 8	• As a result of the triggering of some equipment in the PTG, very large power movements appear that completely differ from the movements analyzed when

#				
		Scenario type	7 – 12 Moderate	planning the functioning of the NPS; • The risk of overloads on important lines and transformation units, including interconnection lines, and the risk of cascading faults occurring increases; • A separation of the system may occur and certain areas may function in island mode; • Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants. This causes the limitation or total loss of reserves; • Major deviations of the NPS functioning parameters are recorded; • The N-1 safety criterion is no longer met; • Also, the low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS; • There is a major risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
5	Unwanted power movements	Likelihood	3 Medium	• Very large power movements appear that completely differ from the movements analyzed when planning the functioning of the NPS; • The risk of overloads on important lines and transformation units, including interconnection lines, increases; • System operation is hampered by large forecasting errors and
		Gravity/ Impact	5 Very high	
		Risk level	15	
		Scenario type	13– 16 Bad	

			cascading equipment triggers and even loss of control over a grid area may occur; • Disturbances can affect all energy markets in the region or across Europe, namely the functioning of the interconnected systems of ENTSO-E members; • Forecast errors/imbalances in different control blocks can lead to incidents/frequency deviations in the synchronous grid area; • Limitations of energy imports/exports may occur; • Extensive damage may occur leading to the failure of supplying electricity to a large number of consumers.
6	Serial faults of equipment	Likelihood — 2 Low Gravity/Impact — 3 Medium Risk level — 6 Scenario type — 4 – 6 Low	• Improper operation behavior of multiple equipment leads to equipment triggers or equipment damage. Some equipment is also accidentally withdrawn from operation for remediation or verification; • The N-1 safety criterion is no longer met; • Separation of a grid area may occur where there are not enough production units to ensure consumption of the area; • Deviations of functioning parameters of the NPS outside the permissible limits shall occur; • Difficulties may arise in carrying out faults remediation work in substations, caused by the large number of equipment of the same type affected and the lack of equipment in security stocks;

			- Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged assets; - There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
7	Human errors	Likelihood: 3 Medium Gravity/Impact: 5 Very high Risk level: 15 Scenario type: 13–16 Bad	- The risk of overloads on important lines and transformation units, including interconnection lines, and the risk of cascading faults occurring increases; - A separation of the system may occur and certain areas may function in island mode; - Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants. This causes the limitation or total loss of reserves; - Major deviations of the NPS functioning parameters are recorded; - The N-1 safety criterion is no longer met; - Also, the low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS; - There is a major risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
8	Strikes, riots, protest actions of employees	Likelihood: 2 Low Gravity/Impact: 4 Very high	The lack of staff leads to a decrease in fuel reserves for power plants, the quality of operating services decreases, the intervention

		Risk level	10	time for repairing faults increases, and some maintenance works are stopped;
		Scenario type	7 – 12 Moderate	

- Due to the low number of staff there is a risk of mistakes due to insufficient training of the available staff or fatigue;
- Problems arise in forecasting consumption on the energy market due to the unpredictable nature of the protest events;
- The occurrence of accidental events in the NPS may lead to extensive damage in the context of lack of qualified staff.

9	Unusually large errors in the forecast of power produced in renewable energy plants	Likelihood	2 Low	There is a positive or negative imbalance between the forecasted power and that which can be produced in renewable energy plants;
		Gravity/ Impact	4 High	
		Risk level	8	
		Scenario type	7 – 12 Moderate	

- There is a positive or negative imbalance between the forecasted power and that which can be produced in renewable energy plants;
- Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers;
- Reduced production in certain plants leads to large power movements to deficient areas and results in voltage deviations and difficulties in compensating reactive power;
- For certain time intervals problems arise in ensuring that the N-1 safety criterion is met;
- Low production level and loading of certain lines as well as low inertia level can lead to the impairment of the static and dynamic stability of the NPS;
- In conditions of low production in power plants

			and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
10	Pandemic	Likelihood: 1 Very low Gravity/ Impact: 1 Very low Risk level: 1 Scenario type: 1– 3 Very low	• Operational staff at dispatch centers, power substations and power plants is affected and lead to an acute shortage of qualified staff necessary to ensure the safe functioning of the NPS; • Also, the lack of staff at all entities in the NPS leads to a decrease in fuel reserves for power plants, the increase of the intervention time for repairing faults, the cessation of maintenance works; • Due to the low number of staff there is a risk of mistakes due to insufficient training of the available staff or fatigue; • Problems arise in forecasting consumption on the energy market due to the unpredictable nature of the pandemic events; • The occurrence of accidental events in the NPS may lead to extensive damage in the context of lack of qualified staff and high intervention time.

2.2. Terrorist attack of the NPS

The identification, assessment and manifestation are shown in Table 2. [7], [8], [9], [22].

Table 2. **Source: Terrorist attack on the NPS**

Risk scenario: TERRORIST ATTACK ON THE NPS			
1	Internal cyberattack on critical infrastructure	Likelihood: 3 Medium Gravity/ : 5	• The attacker (hacker/cracker) acts as an employee of the National Power System (NPS) and

within the National Power System or Power Transmission Grid: power plants, power substations, overhead power lines, dispatchers, etc.	Impact	Very high	disconnects lines, transformers or changes the functioning instructions of some generation units, modifies power reserves, changes the functioning schedule of dispatcher units;
	Risk level	15	
	Scenario type	13– 16 Bad	

- During a cyberattack, it is possible that computer systems may be blocked for use by people other than the hacker or cracker. This affects the possibilities of taking control and restoration measures for the NPS;
- Disturbances occur in the electricity market;
- The disconnection of some production units and equipment within the Power Transmission Grid (PTG) and the Power Distribution Grid (PDG), leads to large power movements to deficient areas and results in the overload of some equipment and voltage deviations and difficulties in compensating the reactive power including during a blackout;
- For certain time intervals problems arise in ensuring that the N-1 safety criterion is met. Also, the low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS;
- In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.

			• The cyberattack may extend to other computer systems belonging to other Transport Operators (TOs) in the region and may lead to the impossibility of receiving or providing support to other countries in the region.
2	External cyberattack on critical infrastructures that are not part of the National Power System or Power Transmission Grid: power plants, power substations, overhead power lines, dispatchers, etc.	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• The attacker (hacker/cracker) penetrates the communication and data transmission computer systems of the energy market participants and acts as an employee working with these systems and manipulating the functioning conditions of the energy market (demands and offers on trading platforms, functioning schedules of production units); • During the attack, it is possible that computer systems may be blocked for use by people other than the hacker or cracker. • Disturbances occur in the electricity market; • Changing the functioning schedule may lead to shutdown of some production units and to the production of imbalances which further may lead to frequency deviations or large power movements towards the deficient areas, voltage deviations and difficulties in compensating the reactive power; • For certain time intervals problems arise in ensuring that the N-1 safety criterion is met. • Also, the low level of production and loading of certain lines may lead to the

			impairment of the static and dynamic stability of the NPS; • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. • The attack may have very serious consequences in the context in which it occurs against the background of high consumption values in the NPS, periods with extremely high temperatures or amid abundant rainfall.
3	External terrorist attack on critical infrastructure within the National Power System or Power Transmission Grid: power plants, power substations, overhead power lines, dispatchers, etc.	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• The attacker (terrorist) destroys technical equipment (lines, transformers, generators, electrical equipment in substations or plants, servers of central command systems, central telecommunications installations).; • In the event of a terrorist attack on power lines, substations or power plants, equipment triggers take place and some equipment becomes unavailable for a very long period of time; • In the event of a terrorist attack on the servers of central command systems, central telecommunications installations, the operation and control capacity of the NPS is being affected in the long run; • Difficulties arise in ensuring that the N-1 safety criterion is met; • Triggering some production

			units and equipment within the PTG and the PDG, leads to large power movements to deficient areas and leads to large power movements to deficient areas and results in voltage deviations and difficulties in compensating the reactive power; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged infrastructures; • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
4	Internal terrorist attack on the management centers within the National Power System or Power Transmission Grid	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• The attacker (terrorist) acts as an employee and disconnects lines, transformers or changes the functioning instructions of some generation units, modifies power reserves, changes the functioning schedule of dispatcher units. These lead to large power movements to deficient areas and result in voltage deviations and difficulties in compensating the reactive power; • Also, the goals of the attacker are the destruction of SCADA - EMS, SCADA - DMS systems, regulator f – P, central control systems, planning and operating systems, IT centers, data storage systems, control command systems from major power substations

			• and plants or telemanagement centers. • Affected management centers can no longer ensure the management, operation or monitoring of installations. This affects the possibilities of taking some control and restoration measures for the NPS; • Disturbances occur in the electricity market; • Large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
5	Sabotage actions by an internal employee on critical infrastructure within the National Power System or Power Transmission Grid: power plants, power substations, overhead power lines, dispatchers, etc.	<table><tr><td>Likelihood</td><td>3 Medium</td></tr><tr><td>Gravity/ Impact</td><td>5 Very high</td></tr><tr><td>Risk level</td><td>15</td></tr><tr><td>Scenario type</td><td>13– 16 Bad</td></tr></table>	• The attacker (saboteur) destroys technical equipment (lines, transformers, generators, electrical equipment in substations or plants) or performs other actions that lead to disconnection or triggers of lines or transformation units, accidental shutdown of the production of groups in power plants; • Some equipment become unavailable for a very long period; • Difficulties arise in ensuring that the N-1 safety criterion is met; • The disconnection of some production units and equipment within the PTG leads to large power movements to deficient areas and results in voltage deviations and difficulties in

		compensating the reactive power; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets; • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.

2.3. Risk scenarios estimation and assessment algorithm

2.3.1. Likelihood Estimation

LEVEL		LIKELIHOOD	Time
	1. Very low	It has a very low likelihood of occurring. Normal measures are required to monitor the evolution of the event.	over 20 years
	2. Low	The event has a low likelihood of occurring. Efforts are needed to reduce the likelihood and/or mitigate the impact produced.	16 – 20 years
	3. Medium	The event has a significant likelihood of occurring. Significant efforts are needed to reduce the likelihood and/or mitigate the impact produced.	11 – 15 years
	4. High	The event has a likelihood of occurring. Priority efforts are needed to reduce the likelihood and mitigate the impact produced.	6 – 10 years
	5. Very high	The event is considered imminent. Immediate and extreme measures are required to protect the objective, evacuation to a safe location if the impact so requires.	1 – 5 years

2.3.2. Gravity Estimation

LEVEL		GRAVITY / IMPACT
	1. Very low	The event produces a minor disturbance in the activity, without material damage
	2. Low	The event causes minor material damage and limited disruption to activity
	3. Medium	Injuries to staff, and/or certain losses of equipment, utilities and delays in providing the service.

4. High	Serious staff injuries, significant loss of equipment of installations and facilities, delays and/or interruption of service provision.
5. Very high	The consequences are catastrophic resulting in deaths and serious injuries to staff, major losses in equipment, installations and facilities and termination of service provision.

2.3.3. Risk Level Calculation

LIKELIHOOD	Very high 5					
	High 4					
	Medium 3					
	Low 2					
	Very low 1					
	0	Very low 1	Low 2	Medium 3	High 4	Very high 5
		GRAVITY / IMPACT				

Note: The risk is given by the product between Likelihood and Gravity / Impact

2.3.4. Risk Scenario Type

Risk level: 1 – 3	Risk level: 4 – 6	Risk level: 7 – 12	Risk level: 13 – 16	Risk level: 17 – 25
Very low	Low	Moderate	Bad	Very bad

3. CONCLUSIONS

Integrated risk-assessment methodologies significantly enhance the resilience of the NPS – By combining technical, organizational, and security-intelligence approaches, a more comprehensive picture of system vulnerabilities can be achieved than with any single method alone. This holistic perspective ensures that risks arising from both operational instability and intentional malicious actions are properly identified and prioritized. **Insecurity in the functioning of the NPS is multifaceted, stemming from both internal system weaknesses and external environmental stressors –** Ageing infrastructure, insufficient redundancy, inadequate maintenance, cyber-physical interdependencies, and human-factor errors all contribute to systemic fragility. Integrated assessment enables early detection of these weaknesses and supports preventive interventions that reduce the likelihood of cascading failures. **Terrorist attacks pose high-impact, low-frequency threats that require specialized assessment techniques –** Unlike routine technical failures, terrorist scenarios demand the integration of intelligence analysis, threat modeling, and scenario-based stress testing. The study confirms that combining physical-security evaluations with cyber-security risk modeling provides a more realistic understanding of attack feasibility and potential consequences;

Interconnectedness increases both system efficiency and systemic vulnerability – Modern NPS networks exhibit tight coupling between power generation, transmission, communication systems, and automated control technologies. Integrated risk analysis shows that failures in one domain – whether due to internal insecurity or external attacks—can propagate rapidly across the system, underscoring the need for unified monitoring and response frameworks. **Building resilience requires coordinated technical, organizational, and policy measures –** Effective mitigation involves not only engineering solutions (such as redundancy, modernization, and hardened infrastructure) but also robust governance mechanisms, emergency response planning, cross-sector communication protocols, and continuous cybersecurity improvements. The integrated approach reinforces the importance of systemic coordination among national agencies, operators, and security services;

Proactive preparedness is more effective and less costly than reactive response – The assessment confirms that early identification of vulnerabilities, regular simulation exercises, and timely investment in security and reliability enhancements significantly reduce the long-term risk exposure of the NPS. Integrated methodologies support decision-makers in allocating resources efficiently to areas with the highest risk-reduction potential. **Integrated risk assessment strengthens national security and public trust –** Because the power system is a critical infrastructure on which all other sectors rely, ensuring its stability and protection from intentional attacks is fundamental to national resilience. A systematic, integrated approach enhances the nation's capacity to prevent, withstand, and rapidly recover from disruptive scenarios, ultimately safeguarding societal continuity and economic stability.

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AN OVERVIEW ABOUT COSTS ANALYSIS OF BATTERIES IN ENERGY TRANSITION

MARIA DANIELA STOCHIȚOIU[1]

Abstract: Storage electricity in batteries is crucial for the integration of renewable energy sources into power grids and for maintaining grid stability. Battery storage plays a vital role in the transition toward a sustainable and reliable energy system, reducing dependence on fossil fuels and contributing to greenhouse gas emission reduction goals in energy transition processes. Battery energy storage is essential for a sustainable energy future and has favorable economic effects.

Key words: congestions, energy transition, battery, sustainable energy development.

1. INTRODUCTION

The global energy transition, although it seems to have entered another phase – with the United States leaving the Paris Agreement, OPEC countries increasing oil production, China building nearly 100 GW of coal-fired power generation capacity – cannot be stopped because the cost of renewable energy is competitive and will become even more competitive (even with storage units).

The integration of prosumers into the grid, both from a technical and commercial perspective, is associated with certain challenges in ensuring the safe and standard-compliant operation of the network, as well as in maintaining a financial balance between prosumers and other consumers connected to the grid, particularly at low voltage levels.[1] One possible solution could be the transition to value-based compensation, regardless of the prosumer's installed capacity, based on Day-Ahead Market prices during the hours when they inject energy into the grid.

It is necessary to set clear national objectives aimed at increasing renewable energy generation capacities, as well as storage capacities, by expanding programs and increasing funding to support energy storage. Romania needs 30 billion euros in network investments by 2050, of which about 15 billion should be needed by 2030.

Prosumers and other distributed energy sources have a substantial influence on the distribution network. Due to the unpredictable nature of energy flows, the grid must become more adaptable, while ensuring that voltage levels stay within acceptable limits remains the primary challenge.[2]

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2. SIGNIFICANCE OF BATTERIES IN ENERGY TRANSITION

To meet the ambitious decarbonization goals established by nations, it is essential to invest in grid expansion, improve the performance of existing renewable energy assets, and enhance the flexibility of the energy system. Enhancing the system's flexibility can be achieved through energy storage solutions for addressing the challenges posed by the intermittent and variable nature of renewable sources, as well as through the provision of subsidiary services. In this context, consumers are encouraging, to take on a central role as prosumers within the energy system, being connected to the distribution grid, generating, consuming, and storing energy through various technologies, while actively participating in energy markets.

Battery energy storage systems are becoming crucial technologies for maintaining the stability and reliability of power grids. These systems enable the storage of excess energy generated during low-demand periods and its discharge during peak demand, while also helping to optimize energy resource utilization, decrease reliance on fossil fuels, and enhance the overall efficiency of energy systems.

The variability of renewable energy sources leads to nonlinear energy production, relying on elements like sunlight and wind speed, which fluctuate over time and across locations [1], [3]. This variation can result in discrepancies between energy supply and demand, potentially causing voltage and frequency fluctuations in the electricity grid, thereby impacting its performance and reliability [4]. In this scenario, battery energy storage systems are crucial, offering an effective method to handle intermittency and maintain a consistent energy supply.

2.1. Benefits

The energy mix in Romania is a diverse combination of hydropower, nuclear, natural gas, coal and growing renewable sources like wind and solar with a strong focus on expanding renewables and reducing coal dependence to meet EU decarbonization targets. Storing electricity in batteries offers numerous advantages. Advantages that enhance both economic effectiveness and the endurance of energy frameworks [5]. These advantages are varied and encompass decreasing energy expenses, steadying rates, enhancing the dependability and adaptability of power networks, advocating for the adoption of renewable energy sources, and generating employment.

3. COSTS OF BATTERY ENERGY STORAGE

Storing electrical energy in batteries involves a series of costs that can be divided into capital costs, operation and maintenance costs, and levelized cost of energy (LCOE). In this chapter, it is emphasizing these cost components and how they influence the economic viability of energy storage solutions.

Economic elements, like the prices of raw materials and market dynamics, can greatly affect the expenses related to battery energy storage. For instance, variations in lithium and cobalt prices, which are crucial elements of lithium-ion batteries, may

influence manufacturing expenses and thus impact battery pricing. Government regulations and subsidy programs are essential in lowering expenses and encouraging the adoption of energy storage technologies. Founds for research and development, tax breaks, and financial assistance programs are crucial for promoting investment and speeding up the widespread use of batteries [6]

3.1. Cost of Capital

Capital costs represent the initial expenditures necessary to buy and set up battery energy storage systems. These expenses are shaped by the kind of battery, energy storage capability, and the utilized technologies. Recently, expenses related to capital for lithium-ion batteries, the most commonly utilized ones today, have dropped considerably. As specified in market literature reported that the average price of lithium-ion batteries has fallen from around 1.100 $/ kWh in 2010 to 200$/kWh in 2025. This significant decline is ascribed to technological progress, economies of scale, along with advancements in manufacturing methods [7]

Residential storage systems generally cost more per unit of capacity compared to industrial or grid stabilization systems because of unique installation needs and the extra equipment needed [5]. Moreover, batteries utilizing alternative technologies, like solid-state or redox-flow, are still in the initial phases of commercialization and entail greater capital expenses, yet they hold the potential for considerable advancements down the line [5].

3.2. Operation and Maintenance Costs

Operation and Maintenance expenses are ongoing costs linked to the functioning and upkeep of energy storage systems. These expenses comprise overseeing the systems, substituting damaged parts, and the costs linked to handling and recycling batteries once they reach the end of their life cycle.

The operation and maintenance expenses for lithium-ion batteries are quite minimal in comparison to other energy storage technologies, owing to their dependability and longevity. The longevity of the battery significantly impacts operation and maintenance expenses. Lithium-ion batteries generally last between 10 to 15 years, influenced by the number of charge and discharge cycles and the conditions in which they operate. Alternative battery technologies like nickel-metal hydride (NiMH) or lithium iron phosphate (LiFePO4) may have varying lifespans, thereby affecting maintenance and replacement expenses.

3.3 Levelized cost of energy (LCOE)

Levelized cost of energy (LCOE) is an essential economic metric that represents the overall cost of energy generation per unit of energy produced throughout a battery's lifespan. LCOE considers all expenses, such as capital, operational and maintenance, and financing costs.

The ongoing decline in LCOE for battery energy storage systems is making them more competitive with conventional energy generation and storage options.

A recent study from speciality literature indicates that the LCOE for lithium-ion batteries has significantly declined in recent years, attaining values about 131-232 $/ MWh, based on the application and system scale. This indicates a decrease of about 70% relative to 2015, underscoring the swift advancement of this technology. In comparison, the LCOE for alternative storage technologies, like hydrogen or pumped hydro, is usually greater, but they can provide benefits in particular situations [5], [6].
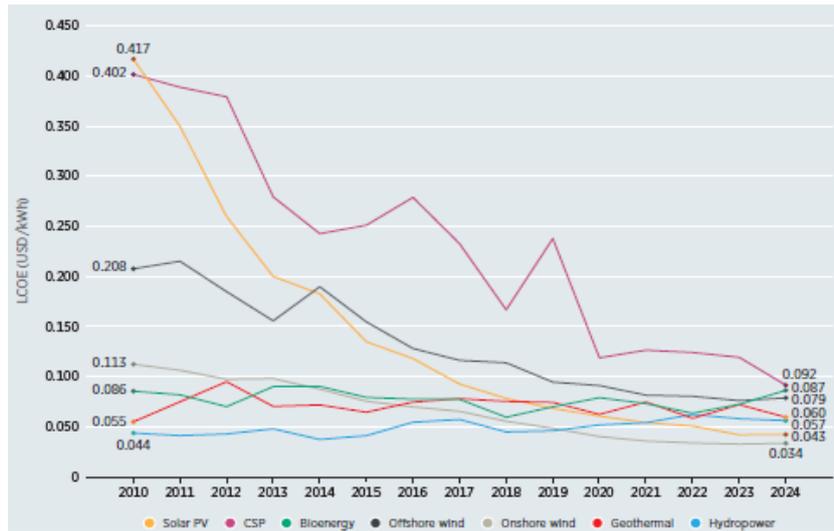
Fig.1. Renewable energy LCOE decline
Source: IRENA (RENEWABLE POWER GENERATION COSTS IN 2024)

4. ADVANTAGES USING BATTERIES

4.1. Reducing energy costs

A primary economic advantage of using batteries for energy storage is the optimization of energy expenses. Batteries enable the accumulation of energy generated during times of low demand and excess, releasing it when demand is high, thereby minimizing the reliance on fossil fuel generators to address peak demands [8]. This results in substantial savings for users and power grid managers.

Storage technologies enable the reduction of energy losses during transmission and distribution, helping to decrease overall energy expenses [9].

4.2. Stabilizing energy prices

A primary economic advantage of using batteries for energy storage is the optimization of energy expenses. Batteries enable the accumulation of energy generated during times of low demand and excess, releasing it when demand is high, thereby minimizing the reliance on fossil fuel generators to address peak demands.

This results in substantial savings for users and power grid managers. Storage technologies enable the reduction of energy losses during transmission and distribution, helping to decrease overall energy expenses [9],[10].

4.3. Improving the reliability and flexibility of electricity grids

Battery energy storage enhances the dependability and adaptability of electricity networks by supplying crucial ancillary services, including frequency and voltage stabilization, load balancing, and management of grid congestion [1],[4]. Batteries can swiftly respond to fluctuations in energy supply and demand, offering a prompt reaction ability that is essential for ensuring grid stability. This minimizes the chances of power failures and guarantees a steady and dependable energy supply.

4.4. Promoting the use of renewable energy sources

A major advantage of battery energy storage systems is to enable the extensive adoption of renewable energy sources. The inconsistency of renewable energy sources, like solar and wind, poses a significant challenge to their broad adoption [5],[9]. Batteries enable the accumulation of energy produced from renewable sources when production is high and its availability in times of increased demand or minimal output, thereby optimizing the utilization of renewable energy and decreasing reliance on fossil fuel energy sources.

4.5. Jobs and Economic Development

The advancement and implementation of battery energy storage technologies generate considerable employment prospects across multiple sectors, such as research and development, production, installation, and maintenance. The energy storage sector knows economic development by investing in infrastructure and technological advancements, thus fostering economic growth and enhancing global competitiveness. The rising demand for lithium-ion batteries has resulted in substantial investments in production facilities and research, generating employment and fostering regional growth [10].

5.CONCLUSIONS

Battery storage, hybrid power systems, and digitalisation are vital for advancing the energy transition and integrating variable sources such as solar PV and wind. Large-scale battery deployment is essential to build a renewable-based power system, with storage expected to deliver most short-duration flexibility needs. Energy storage in batteries plays a crucial role in the shift towards a sustainable and dependable energy system. This technology presents various economic advantages, such as lowering energy expenses, stabilizing prices, and enhancing the reliability and adaptability of electricity grids. Additionally, battery energy storage supports the widespread incorporation of renewable energy sources, lessening reliance on fossil

fuels and helping to achieve goals for reducing greenhouse gas emissions. Although the initial capital investment is substantial, it has significantly decreased due to advancements in technology and economies of scale, making storage technologies increasingly financially feasible. Operating and maintenance costs remain relatively low, and the ongoing decline in the levelized cost of energy (LCOE) highlights the growing competitiveness of batteries in comparison to traditional options.

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ENERGY SECURITY - RISKS AND RESILIENCE OF THE ENERGY SYSTEM IN ROMANIA

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Abstract: The paper reports the results of research conducted through studies on critical situations, mismatches, strategy deficits and tactics with reference to Romania's energy security, the geo-technological and strategic safety of the exploitation of hydrocarbon resources in the Romanian coastal area of the Black Sea, and renewable resources. In the energy field, the systematization of critical situations and mismatches is essential for ensuring the stability and efficiency of the system.

In a concrete contextual sense, the energy strategy is considered an "integrating matrix".

The article deals with the risk in the power supply system and the resilience of the energy system, as well as the modeling of energy events with high impact and low probability.

The transition to new modern practices for the formalization of energy security in the Romanian National Power System is operationalized, also targeting the related resilience, and is materialized through digitalization and automation, flexibility through energy storage, modernization of networks and infrastructure to reduce losses, improvement of regulations and market mechanisms, emergency plans and cybersecurity for critical infrastructure.

Key words: energy security, geo-technological security, strategic security, resilience, fossil fuels, renewable energy, onshore/offshore resources.

1. INTRODUCTION

Energy security, including geo-technological for Romania, is a complex concept that combines energy security, geopolitics and technology to ensure stable and

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sustainable access to energy resources when the existence and influence of risks to operation are established [26], [27], [30].

This implies in a global context alignments such as:

- *Energy security*. Aims at diversifying sources, infrastructure resilience and increasing the share of green energy (renewable energy) to reduce dependence on fossil fuels.

- *Energy geopolitics*, which involves control over oil, gas and critical minerals and which, in fact, influences international relations. The competitiveness between the USA, EU, China and Russia on the energy market and green technologies is a prerequisite for the new energy cold war.

- *Emerging energy technologies* envisage promotions for green hydrogen (alternative to fossil fuels), energy storage.

- *Digitalization* involves optimizing consumption and securing networks through Artificial Intelligence.

Regarding energy security, it is conclusive to identify the threats and challenges that mainly refer to cybersecurity, [5], [18], [22] (cyber-attacks on electrical networks or oil infrastructures), as well as climate change, [16] (climate impact on energy production).

These are joined by the raw materials crisis, [20], [23] (energy, mining) which refers, in particular, to the dependence on rare materials for green energy (lithium, cobalt, cadmium). General strategic development in Romania, by amplifying the activities of valorizing mineral/energy resources from the soil and subsoil, from the marine environment, can take place when tactical practices (underground mining technologies and quarries, onshore and offshore geological deposits) have the potential for effectiveness, operationalization under conditions of resilience in the face of risks and various challenges [28], [33], [36].

Relying on endogenous, own forces in inducing a strategic evolutionary vector with a relevant level of certainty, reliability and feasibility for Romania does not mean autarky, or isolation or investment self-separation.

As such, endogenous strategic resources alone, including geo-technological ones, do not offer the agreed set of properties of strategic energy sufficiency and therefore, in an overall view, interconnection and energy links are promoted, especially for investments at the national, European and global levels.

2. SYSTEMATIZATION OF CRITICAL SITUATIONS, INCONSISTENCIES

In the energy field, the systematization of critical situations and non-correlations is essential to ensure the stability and efficiency of the system.

Structuring the main critical situations and non-correlations refers to:

- *Critical situations in the energy system:* imbalances between production and consumption, production deficit, major technical failures such as damage to the transport and distribution infrastructure (high-voltage lines, transformers, interconnection stations), failures in power plants (thermal, hydroelectric, nuclear, renewable), failures of SCADA and automation systems, variability of production from

wind and solar sources, lack of storage capacity to balance renewable energy, natural gas or oil crisis - impact on thermal power plants, logistical problems in the supply of coal or other resources. Also among the critical situations are cyber attacks on industrial control systems (ICS/SCADA), critical infrastructure security, etc.

- *Misalignments in the energy system*, which refer to inconsistencies between demand and supply, lack of flexibility in adapting production, lack of rapid responses to frequency and voltage fluctuations, insufficient storage capacity or regulation of energy flows, insufficient infrastructure for the transport of renewable energy, inefficient renewable production forecasting system, energy policies not aligned with EU states, tariffs and market mechanisms that do not reflect the reality of demand and supply, delays in the development of new infrastructure, insufficient financing for the modernization of the energy system [29], [35].

For the domestic energy situation, based on the analyses carried out to exemplify the levels and challenges of risks and resilience in the energy system in Romania, the critical alignments on which short and medium-term action is proposed for remediation are presented below.

− Priorities for Ensuring Romania's Energy Security, [19] include themes, topics, objectives, activities and actions that present an aggregate deficit of: 1) assumed vision, 2) real strategy, 3) legislation, 4) plans and programs, 5) sources of financing.

− Closing the coal mines in the Jiu Valley and Oltenia [10]. In particular, on average the cost of a ton of coal from the Jiu Valley underground reaches 70-75 Euro/ton and is sold for 53 Euro/ton (the difference being subsidized by the public budget), while the average international price for imported coal is approx. 60-70 Euro per ton of coal equivalent. The Romanian state pays subsidies of hundreds of millions (billions, over time) of Euros in an area with questionable mining efficiency. Currently, the last mines (Lupeni, Livezeni, Lonea) are in liquidation. The deficit of strategy and vision after 1989 until now is also linked to the fact that in the Oltenia Carboniferous Basin, the Rovinari, Turceni and Işalnița thermal power plants were retrofitted with external credits to use fuel with a calorific value of approx. 1600 kcal/kg from lignite mines and quarries. The underground lignite mines are closed. The lignite quarries are closing, and the CETs in the area no longer have sufficient fossil fuels, they do not have methane gas combustion systems. Mining and energy employees are being laid off, with compensatory salaries and the anthropogenic environmental effects are serious, with land and groundwater disturbed by the overburdening [3], [24], [34].

− The nuclear power units at the Cernavoda NPP, [15], in the CANDU system, in number of 3, are unfinished, and Unit no. 1 the oldest in operation, requires either refurbishment or permanent shutdown.

− The uranium mines in the Băița Bihor area, in the Oravița-Ciudanovița area are closed or in the process of closing (Crucea mine) [8]. The Uranium Preparation Plant in Feldioara will reduce its activity until it is shut down. The deposits in Grințieș, Bicazul Ardelean have expressed interest in exploitation.

− The Hydroelectric Units, [12], are late for completion/commissioning.

− The deposits and production of crude oil and natural gas in Romania, owned/managed by OMV Petrom, [6], have an irreversible decrease in the resource base through exploitation/depletion.

− Refineries, storage and transportation systems for hydrocarbons still do not offer options and alternatives for reducing/eliminating imports, dependence on energy resources from other countries.

− A firm Strategy/Program for the exploitation of geothermal energy must be formulated.

− The application of thermosolar technology for buildings of all categories is not sufficiently promoted.

− The application of photovoltaic technology for buildings of all categories is not sufficiently promoted and applied throughout the country. The "solar tower" technology is not promoted in any case.

− Wind technology is insufficiently developed in areas of Romanian maritime waters (Black Sea).

− Not enough attention is paid to the Circular Economy for Energy from Waste, [3], although Romania is critically facing the waste problem, [13], and there are prospects of interest for methane hydrates on the bottom of the Black Sea [7], [25].

− The geo-technological and strategic security of the exploitation of energy and mineral resources in Romania is affected by critical technological and tactical situations in offshore exploitation in the Romanian coastal area of the Black Sea [2]. The Offshore Law was drafted, [17] and then GEO No. 114/2018 was issued, which raises different views regarding the feasibility and economic viability of investments.

− The provisions found in the current Offshore Law mainly cause specific attitudes among investors with reference to the trading of natural gas through the stock exchange.

− The requirement to perfect and improve offshore legislation is recognized so that companies have investment security and predictability.

− In the context, there is: stagnation and lack of offensive for collaborations, cooperation, attracting investments, insufficient managerial capacity in the field, physical and moral wear and tear of the National Energy System of production, transport, distribution, reduced research for the identification of new energy deposits and resources [11], [31], [32].

3. POWER SYSTEM RISK AND ENERGETIC POWER SYSTEM RESILIENCY

In our opinion, in order to understand the risk in the power system and the resilience of the domestic energy system, in order to formalize results that can be used for countermeasures, it is necessary to present some characteristics in relation to some considerations such as:

− About the risk of the Energy System (in the System) / Production / Distribution of Electricity [4];

− About the resistance / resilience to damage / shock of the Energy System / Production / Distribution of Electricity;

− Correlations, dependencies, conditionality, articulations, compositions between "risk" and "resistance / resilience to damage / shock" in / of the Energy System / Production / Distribution of Electricity.

In this context, a model-based, inclusive-neutral and iterative/reiterative treatment of risk and resilience issues in the national energy system is envisaged, mainly through the following aspects:

− Introduction to Power System Stability (stability categories);
− Clustering of power system stability classification;
− Correlations, dependencies, conditionality, articulations, compositions between power system stability, security and reliability;
− System security assessment with solutions to the transient stability problem;
− Simulations of dynamic responses of the power system (PS);
− Formalization of tangible behavioral characteristics of the Power System to shock/event demands, with reference to the ratio between the influence of various uncontrollable variables manifested for the failure, by shock/event of the Power System and the initial value of the safety/resistance footprint in which the respective failure occurred;
− Protective relocations in the PS;
− Improving transient stability to oscillations of local and inter-zonal modules in the Production/Distribution of Electricity;
− Event description (causes of outages, lessons learned, application of controls, defense plans, restoration plans, online security assessment, reliability management, real-time monitoring and control, dynamic risk-based security assessment);
− Energy system risk management in a multi-objective framework (hybrid fuzzy method and simulation);
− Use of genetic algorithms and Artificial Intelligence;
− Conflict risks in ES;
− ES resilience metrics;
− Metric development by identifying objectives, measurement characteristics, comprehension, understanding, practice, non-redundancy;
− Defensive, transparent and repeatable metrics;
− Development of a resilience indicator through major components such as preparedness, mitigation measures, response capabilities and recovery mechanisms:
− Incident management and ES command, recovery, restoration mechanisms;
− Managerial risk in SE.

In SE management, risk assessment is distinguished between two alignments that refer to the decision-makers' aversion to uncertainties.

Displaying aversion refers to: a) a strong action assumption, a situation in which the alignment is risk neutral and b) an unrealistic/unrealistic action assumption, when the alignment is characterized by an "infinite" risk. Typically, a visible assumption of risk among SE managers occurs when uncertainty is uniformly distributed over the entire problematic area subject to organization and management.

In such a vision, the index of unrealistic risk assumption in SE in absolute value is constant or negative. Thus, new elements of behavioral potential are gained, under conditions of real uncertainty, manifested in the complex, dynamic environment of the Energy System.

The Energy System (ES) as a system objectively evolves due to the time factor, which on its axis displays the entity from one state to another.

The results of classical event management in SE change to the extent that attitudes towards risks are evolutionarily dependent on the trajectory of SE as a system.

Pratt, J.W., (1978/ reed. 2020), [9], and Arrow, K.J., (2012), [14], emphasize that in the context of high risk potential, it is necessary to take into account only attitudes towards small, reduced risks that could be defeated. It is appreciated that this theory, for the contemporaneity positively affected by the generalization of information technologies (including through Artificial Intelligence) that support knowledge in SE, can no longer be accepted absolutely and generally.

On the other hand, boundary-pushing methodologies that allow the perceptible examination of managerial reality in SE create premises for "attacking" medium and large (high) risks.

The method of strategies for close (close) perception of facts subject to evolutions (transformations) in the SE is marked by quasi-continuous feedback information (feedbacks), a situation in which one benefits from the rationalization of behavioral acts towards risks. Usually, in the SE, endogenous aversions (retentions) towards risks are recorded and it is even more possible to manifest excessive aversions, which temper acts of resilience.

The efficient path on which a resistant SE must be found is that of "optimized visible/perceptible trajectories", relying on adaptive behavior.

"Optimal singularity" is the phrase that fits operational SE in the usual epistemological context.

Currently, there are more and more situations in which SE in Romania is confronted with the relative uncertainties of the stochastic dynamic behavior of the energy environment.

The variations of the energy environment are, however, conventionally dependent on the actions exerted on it with the help of the control function.

Therefore, it is found that numerous requirements/decision problems in SE activities are reduced to the essential problem of stochastic control.

Solving optimization problems is a quasi-generalized requirement for all areas in which SE subsystems operate.

A resilient decision in SE adopted is never completely independent and therefore, in connection/connection/articulation with other decisions, it determines SE to find itself implicitly in quasi-permanent risk situations. In such a framework, resilient behavior is a priority and fundamentally important in the face of risks.

As such, managerial risk in SE can be redefined with the degree of confidence in decisions regarding the future as uncertainty erodes. The most efficient method of advancing on this alignment is to increase the predictive power to reduce uncertainties regarding the future behavior of SE as a system.

The quasi-infinite set of contexts generates multiple risk situations.

Even if a new risk or a set of risks is faced, it must be realized that around the risks annihilated in the SE there are other risks, which through a "vacuum" are installed in the area of the managerial issue.

When the objective probability of the risks is measured (has quantified results) it is appreciated that the risks in the SE are formalized and can fall under the incidence of facing.

When objectively appreciated probabilities are not obtained, the risks in the SE have high contents of intrinsic, undeterminable uncertainties. Usually, the aversion to risks in the SE is expressed by the concavity of the utility function.

In the context of the above clarifications, the solution to facing risks in the SE can be done with the help of stochastic evolution scenarios of the SE environment, constantly taking into account the pre-established objectives to be achieved [6].

In the risk management of SE in Romania, classical and neoclassical knowledge become substance for the efficient operationalization of tools against various non-conforming reminiscences of energy activity.

Reminiscences (anamnesis) mark the access to managerial truths, bring back to attention the past ("once") and space ("somewhere"). In the risk management of SE, the theory of reminiscence is associated with the theory of concepts.

The theory of resilient managerial concepts in SE can be considered the last stage of the energy managerial epistemology.

Risk, defined as the variation of potential differentiated outcomes in SE in Romania (variation to which a probability can be associated) is expressed using the formula:

Risk = [the probability of an event occurring] x [the consequences if it occurs]   (1)

Mechanisms for neutralizing risks in the economy are created depending on the risk situation.

The general set of measures to combat the possible consequences of a potential risk in the SE is divided into two groups:

– Preventive measures. (precautionary tasks taken in advance to prevent possible losses in the SE infrastructures, especially in the operational context).

– Compensation measures. (tasks taken to compensate for adverse effects in the event of negative damage to the SE infrastructures).

The perspectives of action complementarity towards the risks of energy damage can be treated modelistically. (fig. 1)
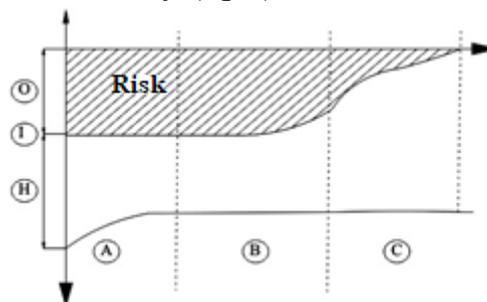
Fig.1. Delimitation of operational areas in the event of risk in SE in Romania
I = uncertainty; O = opportunity; H = hazard;
A; B; C = operational areas in SE.

At the same time, in our opinion, a pre-computerized mathematical/symbolic model associated with a Model of Reconsideration of Management Methods and Techniques in the Field of Unpredictable Events in SE in Romania must be created, through the Bayesian, descriptive, and deterministic approaches, as well as dynamic, experimental, functional, normative, and operational approaches.

These are joined by the systemic, static, and statistical approaches.

4. MODELING OF HIGH IMPACT AND LOW PROBABILITY (HILP) ENERGETIC EVENTS

From global practice, it usually results that energy events, especially those with high negative impact, generally have a low probability of occurring.

If they occur in the general energy picture, they are characterized by catastrophic states, of high amplitude and with rarely encountered effects.

However, in any strategy in the field it is useful to formalize an at least theoretical, conceptual framework for modeling high-impact events with low frequency, in order to support informed decisions in Energy Systems (ES).

In this paper, we address the research alignments for such situations and indicate that we start from the systematization of a matrix of dangerous events (natural and/or man-made) that lead to the loss of network infrastructure or cause damage to the security and resilience of electrical networks.

In this context, the planning and allocation of "emergency" resources, appropriate for such events, will be mathematically formalized in order to quantify the understanding of their probability and the extent of their potential impact.

When events are of low probability, an informal and/or informed perspective on risk is required for planning, as there is no statistical basis for directly estimating the probabilities and consequences of their occurrence in the ES. Specifically, a symbolic, pre-computerized mathematical model will be developed to support the modeling of risk associated with high-impact, but low-frequency events.

A range of hazards/threats to the integrity of the ES infrastructure can be considered, an understanding of their probability of occurrence, and a methodology for addressing vulnerabilities in the ES's critical assets in the face of such events is developed.

The model resulting from the integration of these elements allows for sensitivity assessments based on optional risk management strategies in the ES.

For the case of the Romanian Power System, mathematically expressed investigations and results on the role of systemic resilience, preparation for high-impact and low-probability events and the consequences of prolonged disruptions in the SE are taken into account. At the same time, it is useful to systematize the conceptual and general technical paradigms for the development of risk models in the SE. In fact, the clustering of model classes is performed for the modeling framework approached. Basically, the main components of the SE risk modeling framework are iteratively approached, namely the characterization of hazards and events in the SE, the relevant SE attack factors and the level of vulnerability to such factors, the consequences of the loss of different combinations of network assets in the SE.

Risk modeling, in this context, in the National Energy System involves:

– hazard identification and their probabilistic characterization in the SE (associated event frequencies);

– initialization of the development of events in the SE (selection of representative events for analysis);

– quantification of the infrastructure response (probabilities of asset failure in the SE);

– assessment of the consequences (power outages);

– integration of the model for the development of risk profiles in the SE.

Basically, a matrix of hazard classes is developed in association with a matrix of asset classes. This combination will be found in the model highlighting the SE assets that are potentially vulnerable. In fact, the probabilistic characterization of the degree of hazard in relation to the resilience of the SE is quantified.

Then, an algorithm is developed to estimate the frequencies of triggering events in the SE based on the comparison of hazard curves (source hazard) and quasi-discrete events characterized probabilistically from which resilience scenarios will be generated. Through this article, we propose the establishment of a Platform for the implementation and integration of the model that allows the flexibility of the personalized approach in the Romanian Energy System.

The evaluation of safety alternatives in the SE involves taking into account future events, which could have more than one outcome.Measuring resilient knowledge also means making assessments regarding the probability that certain events will occur in the future in the SE.The probability of events in the SE can be affected by external or internal changes in the energy environment.

In this way, efforts are measured and known to minimize possible factors that may be associated with risks in the SE, or to develop mechanisms to reduce risks when they occur in the SE. Possible risks and uncertainties in the SE, in general, can be grouped, for example, according to their type. Before starting the analysis of future results, for new support infrastructures for the safety of the SE, it is considered important for Romania to clarify the relevant terms of the current energy resilience flow, grouped as follows:

– *Risk,* defined as the variation of possible outcomes in the SE, to which a probability can be associated;

– *Uncertainty*, which manifests itself in the lack of knowledge regarding the probability distribution of events in the SE or future outcomes;

– *Probability,* as a statistical value, relying on the characterization of the possibility of an event occurring in the SE.

Finally, a Risk Neutralization Management Model in the SE can be developed.

5. THE TRANSITION TO NEW MODERN PRACTICES FOR FORMALIZING ENERGY SECURITY IN SEN ROMANIA

For any present situation S_p of the energy security state, an operator ∂ is applicable to redefine the elaboration process towards a different situation S_p^1:

$$S_p \xrightarrow{\ \partial\ } S_p^1 \tag{1}$$

The above relationship is motivated by programmed developments for energy security supported by the Developmental Theory–in–Action [1].

Current practices in relation to new energy technologies / including the involvement of renewable resources (solar, solar thermal, wind) highlight dynamic evolutionary situations in the Romanian National Power System.

The combination of pre-established energy development scenarios with new energy security technologies at the national level always signifies the dominance of the latter, which determines superior situations of the type depicted by the relationship above.

6. CONCLUSIONS

The solutions for managing critical situations and mismatches in SEN Romania, also aiming at the related resilience, are realized through:
- digitalization and automation (SCADA, IA for forecasting);
- flexibility through energy storage (batteries, hydrogen, P2X);
- modernization of networks and infrastructure to reduce losses;
- improvement of regulations and market mechanisms;
- contingency plans and cybersecurity for critical infrastructure.

This systematization for SEN Romania can be expanded depending on the specific context of the targeted energy system.

Future trends for geo-technological energy security for Romania focus on alignments such as:
- increasing investments in energy through the exploitation of onshore and offshore natural gas;
- increasing investments in new generation nuclear energy;
- developing smart and decentralized grids;
expanding renewable energy (solar and wind) on a national scale.

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ANALYSIS OF OCCUPATIONAL RISKS FOR THE JOBS "PHOTOVOLTAIC PANELS INSTALLER", "INDUSTRIAL ROBOT OPERATOR" AND "FORKLIFT OPERATOR" AT ALTIUS PHOTOVOLTAIC LLC GIURGIU

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Abstract. This paper aims to identify, assess and treat the risks of occupational accidents and diseases for workers within S.C. Altius Fotovoltaic S.R.L., Giurgiu, as well as to identify the prevention and protection measures necessary to create a safe working environment. The aim is to highlight the importance of occupational risk assessment within the company. By highlighting the importance of occupational risk assessment, the paper underlines the employer's responsibility to ensure a safe working environment, which promotes the well-being of employees and contributes to the sustainable development of the company. This approach not only protects the company's human resources, but also contributes to the long-term success of the company under investigation.

Key words: Photovoltaic panels, industrial robot operator, accident at work, occupational risk assessment and management, hazard mitigation.

1. INTRODUCTION

The basic step in optimizing the prevention of occupational accidents and diseases in a technical or work system is the identification and analysis of risks in that system; such an analysis allows for the prioritization of risks according to their size and the efficient allocation of resources for priority measures [1], [2].

Methods for risk assessment need to be as univocal and precise as possible to differentiate the risk level of various activities. In this light, we need to reduce the uncertainty in estimation of qualitative attributes such as "*severity*" and "*likelihood*" [3]. The quantified tool presented and applied in this work enable risk assessors to scale their appreciation of the severity of accidents and the factors that influence the occurrence of an accident scenario. This practice improves the transparency of the risk assessment process [4], [5].

Companies can also comply with nationally imposed legislative and regulatory requirements [6], [7], [8], [9].

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S.C. Altius Fotovoltaic S.R.L. from Giurgiu was established on 10-08-2001 and has as its main activity the CAEN code 2611 - ***Manufacture of electronic subassemblies (modules)***. The company is part of the Bomax group which has built its own photovoltaic parks for the production of electricity and also wind farms, being the result of an investment of 8 million euros, half of which is private contribution and the other half is state aid. The construction of the factory took approximately 15 months.

The first photovoltaic panels were produced in Giurgiu in 2012. The factory had a capacity of 33 MW/year, which meant the production of 110 thousand items, and was to double its production capacity starting in 2014, being at that time the only producer of solar panels in Romania and among the few in Eastern Europe [10]. The full range of photovoltaic panels is produced, both monocrystalline and polycrystalline, and items requested by customers are designed on order. For the production of the panels, the necessary materials are imported from Taiwan and from European Union states, with only the aluminum frames being purchased from Romania, from Alprom Slatina. The technological line is state-of-the-art, semi-automatic, and the equipment is manufactured by leaders in the field from Germany, Japan, Italy and Finland [11].

Photovoltaic panels manufactured in Giurgiu comply with European standards and are guaranteed to operate for up to 30 years. The manufacture of panels consists of assembling batteries of cells mounted in series and encapsulating them in the most efficient way possible, so as to meet the operating requirements in a hostile external climatic environment, by hot-lamination of a sandwich formed by five materials placed in layers:

- glass;
- EVA (Ethylene Vinyl Acetate) film;
- series-connected cell battery;
- second layer of EVA film;
- backsheet film.

This formed assembly is framed in an aluminum frame. The performance of the laminator in the company's equipment, as well as the high-quality materials such as EVA foil (made in Spain), ensure the marketing of a high-quality product. The main suppliers of the investigated company are: Sotrafa S.A. Spain, Panasonic, Alprom Slatina and the main customers: Electricom S.A., OMV Petrom S.A, Aggreko South East Europe LLC as well as a significant number of household customers.

In developing the organizational structure, the management team must take into account that there is no ideal organization and no universally valid rules. The best organizational structure is the one that best meets the current needs of the company [12].

The organizational and personnel structure of Altius Fotovoltaic consists of 30 people including:

i. ***TESA body*** which includes:
- General Manager;
- Technical Production Manager;
- Economic Manager;
- Personnel, Human Resources and Procurement Department.

ii. ***Executive staff*** includes:
- Industrial robot operator;

- Subassembly assembler;
- Photovoltaic panel installer;
- Forklift operator, manager, etc.

The organizational structure having a dynamic character, changes are not only inevitable, but also typical. The adaptation of the structure is done according to the internal needs and the human resources that the company has. The organizational structure must be oriented on key activities to obtain key results.

2. DESCRIPTION OF THE FACTORY AND TECHNICAL EQUIPMENT

Within Altius Fotovoltaic LLC Giurgiu, the work process aims to operate with industrial robots, assemble subassemblies for the manufacture of photovoltaic panels. The factory is arranged in an industrial hall with a total area of 2500 sq m, having a height of 7 meters (figure 1). The construction is metallic consisting of truss beams and sandwich panels. The roof is built of sandwich panels. On the east and west sides of the hall, double-glazed windows are installed through which natural light enters the hall.

Fig.1. Industrial hall for the manufacture of photovoltaic panels: overview

Personnel access to the hall is on the north side of the building directly from the company yard. The access routes from the factory yard and inside the production hall are concreted, properly marked and comply with the regulations in force. The floors of the hall are concreted. The access road to the company is paved.

The lighting is provided at night with 2x56 W lighting fixtures placed in sufficient number (55 pieces), and during the day it is mixed (natural and artificial). The microclimate can be ensured, both in winter and summer, with the help of YORK type air conditioning installations (2 pieces). In the case of periods with high temperatures, the staff benefits from mineral water or reduced working hours, depending on the decision of the company management.

The manufacture of panels consists of assembling batteries of cells mounted in series and encapsulating them in the most efficient way possible, so as to meet the operating requirements in a hostile external climatic environment, by hot-lamination of a sandwich formed by five materials placed in layers. This formed assembly is framed in an aluminum frame (figure 2).

Fig.2. Manufacturing of photovoltaic panels: execution details and overview

The technological line is state-of-the-art and consists of the following production means:

a. ***EVA/TPT sheet cutting and laying machine*** (Figure 3): used for automatic cutting and stretching of the second EVA film and backsheet in the solar panel production line.

Fig.3. EVA/TPT sheet cutting and laying machine

b. *BURKLE type laminator* (figure 4)

Fig.4. BURKLE type laminator

The laminator is one of the productions means that is of particular importance in ensuring the quality of photovoltaic panels. It consists of several modules:

- *loading module* where the worker loads the materials for lamination via a belt conveyor;

- *vacuuming and pre-lamination* – seals the layers via the vacuum function to remove air. The product is then pre-laminated quickly and efficiently by thermal transfer;

- *hot press for final lamination* – completes the lamination started in the previous module. Also in this step, fast lamination and the best possible efficiency are achieved by heat transfer;

- *cold press* is used for controlled cooling of the laminated product. Possible product defects that may occur during cooling are prevented by the flat press and ensure reliable and consistent production quality

- Batch separation - similar to line loading, a final unloading bin is installed downstream of the cold press. The bin takes the entire batch of modules and separates them for the next belt conveyor, which transfers the products to downstream production processes (Figure 5).

Fig.5. Batch separation downstream of cold pressing

c. ENDEAS solar simulator (figure 6): it is used in the testing process of photovoltaic panels. The module is placed, the cables are connected and in a few seconds, the system provides comprehensive performance information.

Fig.6. ENDEAS solar simulator

3. ANALYSIS AND PRIORITIZATION OF RISKS FOR THE WORKPLACE "PHOTOVOLTAIC PANELS INSTALLER"

3.1. Description of the technological process

The work process aims to design, build and put into operation solar photovoltaic systems for individuals or legal entities with whom the company has collaborative relationships (figure 7).

Fig.7. Construction and commissioning of solar photovoltaic systems

3.2. The component elements of the evaluated work system

a. **Means of production**
- tool kit;
- photovoltaic panels;
- company car;
- portable impact drill;
- angle grinder (flex);
- glue gun;
- PVC pipe;
- electrical conductors;
- telecom signal transmission equipment;
- solder;
- pickling paste;
- T.S.L. locksmith kit;
- measuring and control equipment (ammeter, voltmeter);
- flashlight;
- portable ladder.

b. **The workload:**
- carries out electrical installations at the company's beneficiaries using production means (tool kits, angle grinder, portable drill, chainsaw, etc.) and the individual protective equipment provided;
- periodically checks fuses in the electrical panel and their calibration;
- checks the connections of technical equipment to the grounding installation;
- checks the continuity of the connection of devices to the grounding sockets;
- ensures the proper functioning of the lighting;
- carries out maintenance and repair work on electrical installations, within the limits of the service competence;
- complies with occupational safety regulations relating to the activity they carry out;
- presents themselves annually to the professional examination, occupational safety and emergency situations;
- is responsible for the proper functioning of the electrical installations within the company;
- participates in the execution of all overhaul and repair work on electrical technical equipment carried out by the company's staff or third parties;

- is responsible for the quality of the work he directly performs.

c. Work environment

• the activity is carried out in a closed space, within the beneficiary units and outdoors;

• the temperature and humidity of the air vary depending on the place of the activity and are within normal values most of the time;

• when the activity is carried out outdoors, the temperature and humidity of the air vary depending on the atmospheric conditions;

• the lighting of the work spaces is mixed - natural lighting, supplemented by artificial lighting. For intervention and repair sites where the lighting is insufficient, the installer uses a flashlight.

• the noise level in some periods of the day is high due to the operation of the drill, chainsaw or angle grinder;

• part of the working time is carried out in the passenger compartment of the car, when traveling in the interest of the service.

Based on the application of the INCDPM Bucharest risk assessment method [13], [14], [15], [16] and using the notations with the meanings explained in table 1, the results summarized in the "Photovoltaic panel installer" job evaluation sheet were obtained, in accordance with table 2.

Table 1. **Meaning of acronyms in the risk assessment sheet**

Acronym	Meaning	Acronym	Meaning
WSC	Work System Component	BFR	Biological risk factors
IRF	Identified Risk Factors	FFR	Physical risk factors
RF	Risk Factor	IC	Inappropriate content
MP	Means of Production	PO	Physical overexertion
WE	Work Environment	Ps.O	Psychical overexertion
WT	Work Task	WA	Wrong actions
HF	Human Factor	O	Omissions
MFR	Mechanical risk factors	MFC	Maximum foreseeable consequence
TFR	Thermal risk factors	S	Severity
EFR	Electrical risk factors	L	Likelihood
CFR	Chemical risk factors	PRL	Partial risk level
D	Death	INV	Invalidity
LTI	Lost time injury		

Table 2. **Job evaluation sheet "Photovoltaic panel installer"**

Altius Photovoltaic LLC	**JOB EVALUATION SHEET**	Exposed persons=7
		Exposure length =8 h/day
Job : Photovoltaic panel installer		*Evaluation team*: Evaluator, Installer, Occupational

			Physician, OHS Professional			
WSC	IFR	The specific form of risk factors manifestation	MFC	S	L	PR L
MP	MFR	1. Moving machine parts - flex disc, power drill - catching overall sleeves, catching, cutting upper limbs - cut or crushed wounds on the upper, lower limbs ;	INV II	5	3	4
		2. Grabbing or pulling hands or clothing items (sleeves, ties, scarves, etc.) by power tools being worked with, transmissions through fan/water pump belts, timing belts - cuts or puncture wounds to the hands.	D	7	1	3
		3. Self-locking of the steering mechanism or braking system while driving;	D	7	1	3
		4. Hit by means of motor transport and/or railway, while traveling during and on the normal route between home and workplace or between work points;	D	7	1	3
		5. Free fall of objects from a height (manipulated objects, insulators, tools, branches, etc) ;	D	7	1	3
		6. Projection of bodies or particles when working with power tools (drill, flex), (breaking masonry elements when working with a hammer, chisel, etc.) - eye diseases, facial diseases;	INV III	4	3	4
		7. Cuts and/or puncture wounds to the upper limbs, contact with dangerous surfaces (conductor ends, surfaces with burrs, tools, etc);	LTI 3-45	2	5	3
		8. Crushing of hands, fingers – when handling tools (hammer, chisel, wrench, screwdriver, screwdriver) – crush wounds ;	LTI 3-45	2	5	3
	TFR	9. Accidental direct contact with overheated surfaces in defective situations, recently processed metal surfaces, etc. - thermal burns;	LTI 3-45	2	3	2
		10. High temperature of some surfaces, accidentally touched during inspections and repairs (exhaust system galleries, engine block, etc.) - thermal burn ;	LTI 3-45	2	3	2
		11. Direct contact of the epidermis with cold metal surfaces when working outdoors in the cold season - frostbite, thermal discomfort;	ITM 3-45 ZILE	2	3	2
		12. Thermal burns caused by starting fires;	LTI 3-45	3	3	3
	EFR	13. Electrocution by direct contact in the event of performing work without removing the installation from voltage or due to damaged conductors;	D	7	2	4
		14. Electrocution by indirect contact due to lack of grounding or inadequate grounding;	D	7	1	3
	CFR	15. Flammable substances – fuels, oils, greases, etc;	D	7	1	3

	BFR	16. Worker becoming ill through contact with the COVID 19 virus or other viruses;	D	7	1	3
WE	FFR	17. Exposure to extreme temperatures - high or low air temperature depending on the season - when performing work outdoors - frostbite, respiratory diseases ;	LTI 3-45	2	5	3
		18. Air currents – when working outdoors – rheumatic diseases, respiratory diseases;	LTI 3-45	2	4	2
		19. Low and/or unevenly distributed lighting level when performing interior electrical installation - eye disorders.	LTI 3-45	2	2	2
		20. Natural disasters - earthquake, blizzard, storm, falling trees ;	D	7	1	3
	CFR	21. Inhalation of smoke, in the event of a fire or toxic gases breaking through certain insulations (epoxy resins, PVC, etc.) followed by combustion with or without flame - poisoning, respiratory diseases;	LTI 45-180	3	3	3
WT	IC	22. Suspension of the vehicle, in case of flat tires, using improvised and/or unapproved means ;	D	7	1	3
		23. Storage of materials with which the work is to be carried out, on access routes - dislocations, fractures;	LTI 3-45	2	5	3
	PO	24. Back and lumbar disorders – forced positions when installing panels, fixed position when driving long distances in the company car ;	LTI 3-45	2	4	2
	Ps. O	25. Stress caused by working at height, the possibility of falling - neuropsychiatric disorders;	LTI 3-45	2	6	3
HF	WA	26. Performing unforeseen operations in the work task;	D	7	1	3
		27. Driving under the influence of alcohol, drugs or in an advanced state of fatigue;	D	7	1	3
		28. Performing maneuvers not permitted by the legislation regulating traffic on public roads: overtaking, turning, in areas where these maneuvers are prohibited;	D	7	2	4
		29. Driving without fastening the seat belt	D	7	1	3
		30. Performing maneuvers without ensuring visibility (especially when reversing);	D	7	1	3
		31. Driving with faults in the steering mechanism, electrical system, braking system;	D	7	2	4
		32. Failure to adapt speed to traffic and weather conditions;	D	7	2	4
		33. Exceeding the maximum number of persons allowed, the maximum permitted load;.	D	7	1	3
		34. Stopping the engine on a slope and putting the gear lever in neutral (when descending);	D	7	1	3
		35. Engaging in conversations with passengers or using a mobile phone without a hands-free system;	D	7	1	3
		36. Putting a faulty installation or power tool (drill, flex, etc.) under voltage;	D	7	1	3

		37. Working with faulty tools and appliances (voltage indicators, measuring devices, patents, fuses);	LTI 3-45	2	5	3
		38. Execution of improvisations - conductors of inappropriate section, damaged insulation - placed on traffic routes;	D	7	1	3
		39. Traveling, standing in hazardous areas - on access roads, in working area of lifting equipment, etc;	D	7	1	3
		40. Falling from the same level due to imbalance, slipping, tripping, dislocations, fractures;	LTI 3-45	2	5	3
		41. Fall from height - from ladders, poles or when working at heights;	D	7	1	3
	O	42. Failure to use personal protective equipment and other protective equipment provided (safety helmet, overalls, electrically insulating boots and gloves, safety belt, etc)	D	7	2	4
		43. Failure to comply with the ITP technical inspection schedule of the vehicle.	D	7	1	3

The overall risk level of the workplace is:

$$N_{rg} = (7(4x4)+30(3x3)+6(2x2)/(7x4+30x3+6x2) = 3.15$$

Figure 8 represents the so-called "risk landscape", in this case the histogram showing all the identified risks and the corresponding partial risk levels, and table 3 summarizes the main prevention and protection measures intended to minimize the risks considered to be included - following the assessment - in the field of intolerable risks.
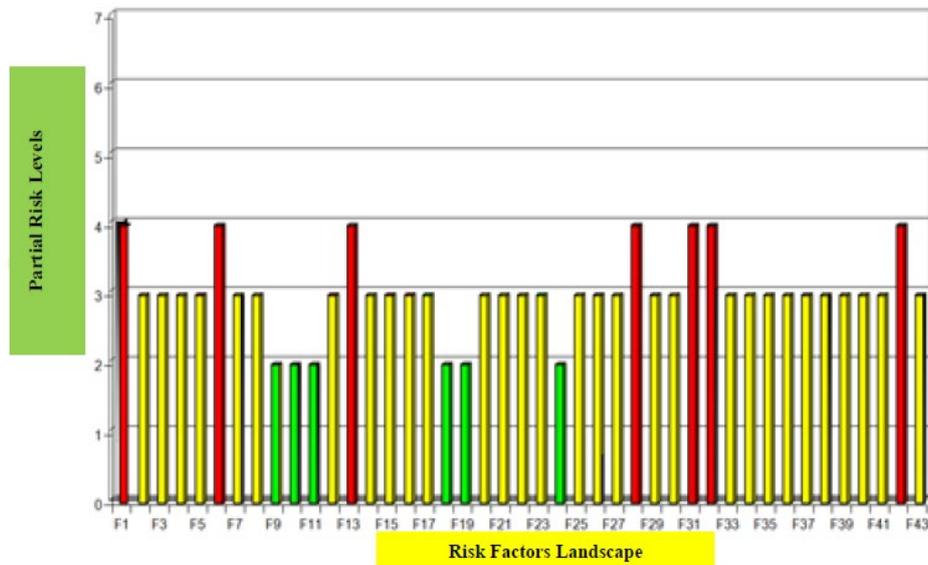
Fig.8. Histogram of partial risk levels associated with individual identified risks

3.3. Proposed measures sheet: Workplace: "Photovoltaic panel installer"

Table 3. **Proposed measures to minimize the identified risks**

Risk factors	Risk level	Proposed measures
Moving machine parts - flex disc, chainsaw chain, power drill - catching overall sleeves, catching, cutting upper limbs - cut or crushed wounds to the upper and lower limbs	4	***Organizational measures:*** Training workers on the risks they are exposed to when working with machines that have moving parts, Verifying the existence of protective guards; Verifying compliance with their own instructions. Presenting first aid measures in case of injuries.
Projection of bodies or particles when working with power tools (drill, flex, breaking masonry elements when working with a hammer, chisel, etc.) - eye diseases, facial diseases	4	***Technical measures:*** Providing protective glasses ***Organizational measures:*** Mandatory use of protective glasses when working with a grinder, chainsaw or electric drill Training personnel on the risks they are exposed to by not using protective equipment when working with a grinder or electric drill
Electrocution by direct contact in the event of performing work without removing the installation from voltage or due to damaged conductors, faulty switches, sockets, plugs	4	***Technical measures:*** Prohibition of putting faulty equipment into operation through safety indicator of prohibition and electrical separation Equipping with appropriate PPE ***Organizational measures:*** Verification of the use of PPE HSE training. Presentation of first aid measures in case of electric shock
Performing maneuvers not permitted by the legislation regulating traffic on public roads: overtaking, turning, in areas where these maneuvers are prohibited	4	***Organizational measures:*** OHS training, processing of own OHS instructions, of the prevention and protection plan, of the provisions of the Highway Code and raising workers' awareness of the risks they are exposed to by not respecting the provisions contained in these documents
Driving with faults in the steering mechanism, electrical system, braking system	4	***Organizational measures:*** OHS training, processing of own OHS instructions, of the prevention and protection plan, of the provisions of the Highway Code and raising workers' awareness of the risks they are exposed to by not respecting the provisions contained in these documents
Failure to use personal protective equipment and other protective equipment provided (safety helmet, overalls,	4	***Technical measures:*** Providing personal protective equipment (electrically insulating boots and gloves, boots, overalls, safety glasses, safety helmet) and other necessary protective equipment

electrically insulating boots and gloves, etc.)		***Organizational measures:*** HSE training Checking the wearing of personal protective equipment and other protective equipment Training staff on the risks they are exposed to by not using the protective equipment provided
Failure to adapt speed to traffic and weather conditions	4	***Organizational measures:*** OHS training, processing of own OHS instructions, of the prevention and protection plan, of the provisions of the Highway Code and raising workers' awareness of the risks they are exposed to by not respecting the provisions contained in these documents
Grasping, driving hands or clothing items (sleeves, ties, scarves, etc.) by fan/water pump belt transmissions, timing belt	3	***Organizational measures:*** Health and safety training Presentation of first aid measures in case of accident
Self-locking of the steering mechanism or braking system while driving	3	***Organizational measures:*** Compliance with the deadlines for carrying out the periodic technical inspection of the vehicle (ITP)
Hit by means of motor transport and/or railway, while traveling during and on the normal route between home and workplace or between work points	3	***Organizational measures:*** Training on the risks and the need to respect traffic rules when traveling on public roads.
Free fall of objects from height (insulators, tools, branches, tiles, trees during deforestation, etc)	3	***Technical measures:*** Equipped with PPE (head protection helmet) ***Organizational measures:*** HSE training. Verification of PPE use.
Cuts and/or puncture wounds to the upper limbs, contact with hazardous surfaces (conductor ends, burr surfaces, tools)	3	***Organizational measures:*** OHS training on handling and working with cutting surfaces
Thermal burns caused by starting fires	3	***Organizational measures:*** OHS and SU training Presentation of first aid measures in case of burns.
Fall from height - from a ladder or when working at heights	3	***Organizational measures:*** Health and safety training Carrying out periodic medical check-ups ***Technical measures:*** Equipped with a quality certified ladder.
Failure to comply with the ITP technical inspection schedule of the vehicle	3	***Organizational measures:*** OHS training Respect for the due date of the Periodic Technical Inspection ITP. Processing the provisions of the Road Regulations

3.4. Interpretation of assessment results

The global risk level calculated for the job "photovoltaic panel installer" is equal to 3.15, a value that places it in the category of jobs with a medium risk level, not exceeding the maximum acceptable limit (3.5). The result is supported by the "Assessment Sheet", from which it is observed that out of the total of 43 risk factors identified, only 7 exceed, as a partial risk level, the value 3. In order to reduce or eliminate the 7 risk factors that are in the unacceptable range, it is necessary to implement the generic measures included in the document entitled "Proposed measures sheet". Regarding the distribution of risk factors by generating sources, the situation is as shown in the diagram represented in figure 9, in particular:

- 37%, factors specific to the means of production;
- 12%, factors specific to the work environment;
- 9%, factors specific to the work task;
- 42%, factors specific to the human factor.

From the analysis of the Evaluation Sheet, it is found that 64% of the identified risk factors can have irreversible consequences on the human factor (death or disability), so that the workplace can be classified among those with a particular risk of injury.
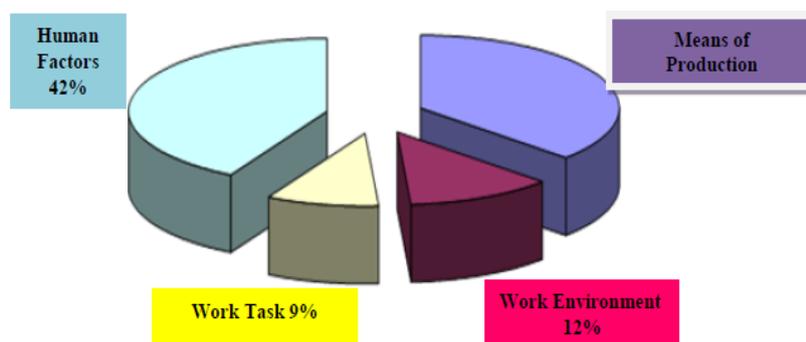
Fig 9. Distribution of identified risk factors by generating source for the job position: "Photovoltaic Panel Installer," with an overall risk level of 3.15.

4. CONCLUSIONS

This research paper targeted a specific aspect of occupational risk management in a Romanian company manufacturing and installing solar photovoltaic panels, namely the assessment, in accordance with the provisions of national legislation in the field, harmonized with the acquis communautaire of the European Union.

To support employers in fulfilling their legal obligations in the field of occupational risk assessment, there are currently many assessment methods that are used, but for the purpose of carrying out the case study, the I.N.C.D.P.M. method of "*Assessment of occupational accident and illness risks at work (workplace)*" was applied, a useful tool in identifying and ranking hazards - and associated risks, which retains its usefulness and purpose as long as it is applied with discernment, attention and by using a balanced and homogeneous balance in the phase of allocating the probability

classes and those of severity associated with the risk factors identified by the members of the assessment team.

The research was based on the analysis of each work station in the field and on the primary documents regarding technology and human resources provided by S.C. Altius Fotovoltaic S.R.L., namely: the content of the work processes for the analyzed places, job descriptions, determination bulletins; statistics of work accidents in the last 10 years as well as the own observations made by the members of the analysis team during the documentation visits, monitoring and tracking of the specific activity for each workplace/work station among those investigated.

The results of the occupational risk assessment by applying the method in the manner presented are presented in the "Job Assessment Sheet" and the "Proposed Measures Sheet" for each analyzed workplace. The list of evaluated workplaces is given in Table 4.

Table 4. **List of evaluated jobs from the investigated company**

Workplace No.	No. sheet	Workplace	Overall risk level
1	F1	Industrial robot operator	2.89
2	F2	Photovoltaic panel installer	3.15
3	F3	Forklift operator	3.00

The overall risk level for the 3 jobs is:

$$N_{gs} = \frac{\sum\limits_{i=1}^{3} Nrg_i \times Nrg_i}{\sum\limits_{i=1}^{3} Nrg_i} = \frac{27{,}12}{9{,}02} = \mathbf{3{,}00}$$

The ranking of places, depending on the overall risk level, is shown in table 5.

Table 5. **Ranking of investigated workplaces according to the calculated risk level**

Workplace No.	No. sheet	Workplace	Overall risk level
1	F3	Photovoltaic panel installer	3,15
2	F2	Forklift operator	3,00
3	F1	Industrial robot operator	2,89

According to the hierarchy, it is found that all workplaces have a global risk level below the allowed limit (3.5), falling into the category of those with a low to medium risk level. The aggregate global risk level of the company, $N_{gS} = 3.00$, confirms this classification, reflecting - to a large extent - the efficiency of the prevention and protection measures implemented within the company. Therefore, S.C. Altius Fotovoltaic SRL Giurgiu falls into the category of companies with a medium risk level.

It can be said that the assessment of occupational accident and disease risks represents a necessary and useful tool for fulfilling the established duties, for the management of Altius Fotovoltaic SRL and for the personnel with duties in the field of occupational safety and health, because it allows the identification of all risk factors,

establishing the size of the risks, which is a mandatory stage for the development of own occupational safety norms and instructions, for the generation of own personnel training materials in the field of occupational safety and health. On this basis, it becomes possible to substantiate a program of awareness of all stakeholders regarding the establishment, development and culmination of a positive culture of risk management, in an initial "top - down" approach, with the consequence of the germination of a participatory approach, oriented "bottom - up" that will complete a proactive organizational security culture, in the spirit of the principles of the ISO 31000 standard.

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ELECTRICITY CRISIS MANAGEMENT: NATIONAL, REGIONAL AND BILATERAL MEASURES

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Abstract: Electricity crises – triggered by supply shortages, infrastructure failures, extreme weather events, geopolitical tensions, or market disruptions – pose significant challenges to economic stability, public welfare, and national security. Effective management therefore requires a coordinated framework operating at national, regional, and bilateral levels. National strategies typically focus on strengthening grid resilience, diversifying generation sources, improving regulatory oversight, and deploying demand-side management tools. Regional measures emphasize integrated power markets, interconnection upgrades, shared reserve capacity, and coordinated emergency protocols to ensure system stability across borders. Bilateral cooperation further enhances crisis response by enabling targeted power exchanges, cross-border infrastructure development, technical assistance, and joint investment in renewable or flexible generation resources. Together, these multi-layered mechanisms provide a comprehensive approach to preventing, mitigating, and responding to electricity crises. This paper examines the interplay among national, regional, and bilateral measures and highlights best practices that can support a more secure, sustainable, and resilient electricity landscape.

Keywords: electricity crisis, national, regional, bilateral measures, blackout.

1. INTRODUCTION

Power systems worldwide are experiencing increasing vulnerability due to rapid fluctuations in demand, evolving generation portfolios, geopolitical uncertainties, and the growing frequency of climate-related disruptions [22], [25], [28]. For many states, ensuring a stable and affordable electricity supply has become a central policy

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priority, as shortages can undermine economic productivity, public welfare, and national security.

The complexity of modern power systems – characterized by cross-border interconnections, diversified energy mixes, and liberalized market structures – demands a multifaceted approach to crisis management [1], [2], [10].

This study examines the strategic frameworks and operational mechanisms employed at the national, regional, and bilateral levels to prevent, mitigate, and respond to electricity crises [12], [14], [16].

National measures often focus on capacity planning, grid resilience, demand-side management, and emergency response protocols. Regional cooperation, particularly within integrated power pools or supranational organizations, enhances collective security of supply through shared resources, harmonized regulations, and coordinated market interventions [17], [23], [27].

Bilateral agreements, meanwhile, serve as flexible instruments for targeted support, enabling electricity imports, mutual assistance, and joint infrastructure development between neighboring states [13], [20], [26].

By analyzing these levels of intervention, this research seeks to illuminate how multi-layered governance structures contribute to electricity security. It explores the effectiveness of different mechanisms, the institutional challenges that hinder coordinated actions, and the evolving role of cross-border collaboration in an increasingly interconnected energy landscape [4], [18], [24].

Through this lens, the study aims to provide a comprehensive understanding of electricity crisis management as both a national responsibility and a collective regional endeavor [3], [5], [11].

2. NATIONAL, REGIONAL AND BILATERAL PROCEDURES AND MEASURES IN THE EVENT OF AN ELECTRICITY CRISIS

The Romanian Power System functions as an interconnected system to the European Power System – ENTSO-E, which represents the European Network of Transmission System Operators for Electricity, according with *figure 1*.

Romania, through the national electricity transmission company, Transelectrica, which is a national transmission and system operator (TSO), has an active and essential role within ENTSO-E, being a full member [15], [19].

It manages and operates the electricity transmission system, ensuring electricity exchanges between Romania and the countries of the European Union and the neighbouring countries that are not part of the European Union (Serbia, Ukraine and the Republic of Moldova).

The National Power System, through the Electricity Power Transmission Grid, is composed of the following critical energy infrastructures [21]:

- 82 power substations (400 kV and 220 kV);
- 8834.4 km overhead power lines (400 kV and 220 kV);
- 216 transformation units totaling 38 058 MVA.
- 1 National Energy Dispatch – NED;
- 5 Territorial Dispatchers – TED.
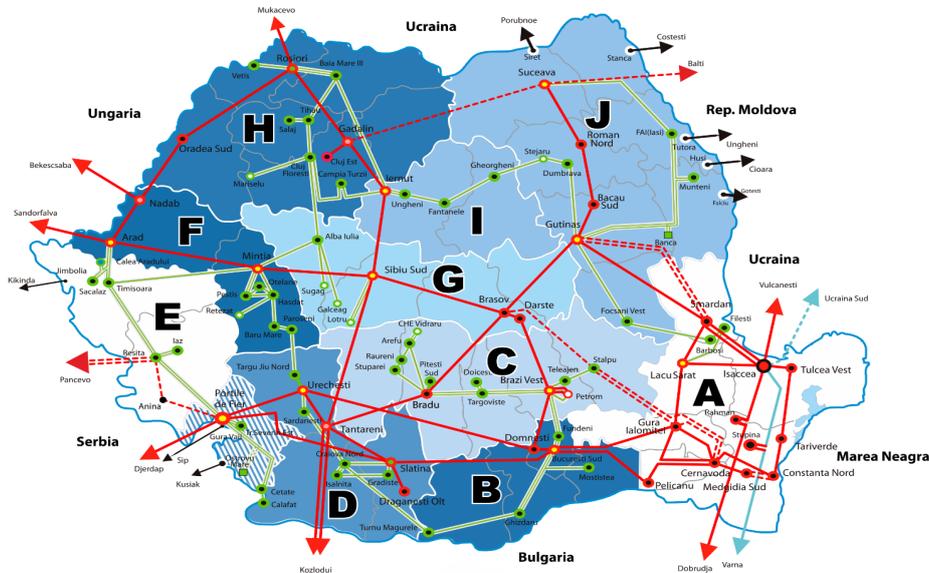
Fig.1. National Power System map (source: Transelectrica)

2.1. National procedures and measures

In accordance with the requirements of the „Law no. 123/2012 on electricity and natural gas" and the „Regulation on technical safeguard measures in exceptional situations arising in the functioning of the National Power System", approved by NAER Order no. 142/2014 a set of safety measures („of safeguard") is established to prevent or limit the effects of exceptional situations that may occur in the functioning of the NPS [6], [7].

2.1.1. Measures regarding the functioning of the energy market

The basic principle of action in the event of a crisis situation is to allow the electricity market to function even in situations when demand and supply are limited and the price of electricity experiences steep variations.

NAER Order no. 142/2014 provides for two categories of measures that apply both by the Transmission System Operator and the Distribution Operators to final electricity consumers supplied directly from the NPS power substations. The first category consists of technical measures without impact on the electricity market, and the second category is technical and commercial measures, of which the last measure in order of application is the limitation of electricity consumption to certain categories of industrial consumers, without resorting to the interruption of their electricity supply.

The consumption limitation/reduction measure is applied in installments, as a measure of last resort, only to those industrial consumers who have the technical possibility of reducing consumption by appropriately adapting the technological process, being conditioned by the issuance of a Decision of the Government of

Romania, at least 5 days before the moment of application and with a prior notification of consumers of at least 24 hours.

The final customers to whom the consumption limitation measures are applied have provided for this obligation in the transmission or distribution contract, as the case may be.

The measure to suspend the electricity market will be taken only in special situations, as a last resort when all the measures listed below have been exhausted, namely:

Measures without impact on the electricity market:

Measures that are applied to prevent a crisis situation in the functioning of the NPS and do not affect the functioning of the electricity market:

- loading the groups to the maximum available power (including starting the groups in reserve);
- increasing the available power of the NPS, by making available the production units under repair (returning to operation ahead of schedule the groups under repair);
- reducing the dispatchable consumption declared as load offer on the balancing market;
- requesting emergency assistance from neighboring TSOs;
- transition to minimum voltage band functioning in the Distribution Power Grid (DPG).

Technical and commercial measures with an impact on the electricity market:

Safeguard measures that apply in crisis situations in the functioning of the NPS – technical and commercial measures that may affect the electricity market:

- increasing the technological system reserves in production units that can function on alternative fuel, in order to use them as appropriate;
- reduction/cancellation of available interconnection capacity in the export direction;
- reduction/cancellation of notified exchanges in the export direction;
- limitation of electricity consumption in installments, under the conditions established by Government Decision and in accordance with the provisions of the Limitations Norm.

Once the crisis has been triggered, the TSO may apply technical and commercial safeguard measures to prevent crisis situations affecting the functioning of the electricity market, namely:

- increasing the technological system reserves in production units that can function on alternative fuel (e.g. fuel oil), in order to use them as appropriate;
- reduction/cancellation of available interconnection capacity in the export direction;
- reduction/cancellation of notified exchanges in the export direction.

2.1.2. Measures regarding manual interruption of consumption

In unforeseen situations that endanger the functioning of the NPS, at the TSO level there is also the possibility of manually disconnecting certain categories of industrial consumers, for a limited period of time, after which these consumers are re-powered at a minimum technological power, so as not to endanger the security of the installations and staff.

The manual interruption of consumption shall be carried out in exceptional circumstances arising in the functioning of the NPS, in accordance with the Operational Procedure (OP) No TEL-07.III AV-DN/24_The method of elaboration and application of the manual disconnection regulations of certain categories of final customers, by instalments, in exceptional situations arising in the functioning of the NPS – hereinafter referred to as "The manual disconnection regulation".

The manual disconnection regulation is applied as a last resort, in situations that could not be anticipated in the functioning of the NPS, situations that endanger the functioning of the NPS or an area of the NPS, in order to prevent the propagation or aggravation of this situation.

The manual disconnection regulation applies to the following exceptional NPS functioning situations:

- transition to isolated functioning of the NPS, after the activation of the automatic device at decreasing frequency, if the frequency cannot be restored and maintained at values > 49 Hz, due to lack of available active power;
- isolation of an area of the NPS, where the frequency and/or voltage cannot be restored to values allowing synchronization of some generating groups or synchronization of the area to the NPS, due to the lack of available active power in the area;
- through the grid supplying an area of the NPS (lines, transformers, autotransformers), loads that exceed the permissible limit values from the point of view of the equipment (thermal limit) occur and these cannot be removed by other measures during the permitted overload functioning;
- in an area of the NPS or in most of it, after all adjustment measures have been taken, the voltages are maintained at values not more than equal to the value of the sacrifice voltage (360 kV for the 400 kV grid, 180 kV for the 220 kV grid and 85 kV for the 110 kV grid) and this situation may endanger the stability of functioning;
- the decrease below the normal limits of the reserve against the static circulation stability limit by a characteristic section through which a deficient area is supplied, until the slow tertiary reserve in that area is started or, when it is missing, until the application of the Regulation limiting the electricity consumption, by instalments, in crisis situations arising in the functioning of the NPS;
- the occurrence of a short-term active power deficit (4 ÷ 48 hours) leading to an hourly deviation from the programmed balance, inadmissible according to the ENTSO-E rules, until the mobilization of the slow tertiary reserve or, when it is missing, until the application of the Regulation limiting the electricity consumption, by instalments, in crisis situations arising in the functioning of the NPS.

All consumers to whom the Manual disconnection regulation and the Regulation for limiting/reducing electricity consumption may apply are industrial consumers, household consumers being excluded.

Also, the number of industrial consumers connected to the PTG is low and do not have special protection against disconnection.

2.1.3. Special protection against disconnection

The manual disconnection regulation applies only to final customers included in the current regulation. These final customers are industrial consumers who, through the technological process used, have the capacity to be disconnected for a pre-established period and then need to be re-powered to the minimum technical power.

The manual disconnection regulation applies until the previously provided conditions disappear, as a result of a change in the situation in the NPS or the successful implementation of recovery measures (mobilization of adjusement energy, commissioning of grid elements) or, when this is not possible, until the application of the Regulation for limiting electricity consumption.

The manual limitation of consumption shall be carried out in foreseeable situations in the functioning of the NPS, in accordance with OP No TEL-07.III AV-DN/13_The method of elaboration and application of the regulation for limiting electricity consumption, by instalments, in crisis situations arising in the functioning of the NPS .

The limitation regulation applies in the following crisis situations of functioning of the NPS:
- national fuel shortages;
- energy deficits, determined by the evolution of the international economy;
- energy deficits, determined by the country's defense needs;
- energy deficits, determined by environmental protection needs;
- energy deficits in a deficient NPS area, determined by the unavailability of production sources in the area and limited grid capacity to ensure the safely transmisision of necessary power from other areas.

The determination of the likelihood of a crisis situation occurring in the functioning of the NPS is made by the TSO on the basis of the short and medium term adequacy analyses of the NPS, taking into account:
- the fuel stocks and the conditions for carrying out the economic activities that provide them (extractive industry, transport);
- the state of the National Natural Gas Transmission System;
- the volume of water reserves in reservoirs;
- the availability of electricity production units;
- the electricity consumption at the level of the NPS or at the level of an area of the NPS;
- the PTG and PDG availability.

Also, at regional and European level, the STA (Short Term Adecuacy forecasts) process is carried out daily for the next seven days by RSCs (Regional Security Coordinator), based on daily analyses for the next seven days.

The regulation for limiting the electricity consumption applies, following the adoption of a Government Decision, as a last safeguard measure taken in crisis

situations arising in the functioning of NPS that may be foreseen in the medium and long term, which endangers the functioning of the NPS or of an area of the NPS.

In critical situations in the NPS, the economic operators included in the regulation limiting the electricity consumption are notified in writing by the TSO on the provision for the application of the Regulation limiting the electricity consumption. The regulation applies only to final customers included in the current regulation. These final customers are industrial consumers who, through the technological process used, have the capacity to reduce their electricity consumption.

2.1.4. Prevention and preparedness measures

Prevention and preparedness measures at the design and planning stage:
- Analysis of the operational behavior of electrical equipment (determination of equipment with high failure rate and elimination of non-conformities).
- Analysis of the operational behavior of the lines (detection of areas where triggers occur frequently due to extreme weather events).
- Imposition of specifications for the purchase of electrical equipment to ensure their proper functioning in the event of low temperatures.
- Imposing, through design regulations increased earthquake safety conditions for lines of maximum importance for the NPS, for substations and control centers buildings, for the foundations of electrical equipment and transformation units.
- Imposing, through design regulations increased safety conditions for lines of maximum importance for the NPS (use of active conductors with low coefficient of expansion, use of pipe with high degree of mechanical strength).
- Use of electrical equipment with composite tires instead of porcelain in areas with high seismic activity.
- Expertise of old generation equipment.

Prevention and preparedness measures in development and investment work:
- Initiation of investment works/major maintenance to diminish galloping effects, improve the insulation level of lines, etc.).
- Replacement of concrete pillars with metal pillars.
- Implementation of the development plan of the Power Transmission Grid.
- Implementation of the development plan of the Power Distribution Grid.
- Installation of monitoring systems on lines.
- Periodic audit and updating/upgrading the safety of computer systems.
- Use of modern and high-performance forecasting techniques based on multicriterial analysis, leading to a robust dimensioning of NPS power reserves.

Preventive and preparedness measures during maintenance work:
- Implementation of the maintenance plan of the Power Transmission Grid.
- Implementation of the maintenance plan of the Power Distribution Grid.
- Implementation of the maintenance plan for electricity production companies.
- Maintenance of control systems.

- Maintenance of system automation.
- Maintenance of automation in power plants
- Maintenance of the automatic device at decreasing frequency, automatic device at decreasing voltage.
- Maintenance of heating systems.
- Eliminating weaknesses and deficiencies in transmission and distribution grids;
- Filling with oil, SF6 gas.
- Eliminating hot spots.
- Equipment operation checks.
- Diesel Groups checks.
- Batteries checks.
- Periodic checks on the condition of the foundations of the pillars in the areas adjacent to river streams.
- Checks on the track of lines where there is a risk of landslides.
- Checking the functioning of the tap-changer switches at the transformer units.
- Maintenance of line safety lanes and removal of dry vegetation from the interior of safety lanes.
- Mowing vegetation inside the substations.
- Maintaining switching equipment (separators) in proper condition to allow handling in conditions of ice formation on contacts.
- Maintenance of substation constructions (concrete channels and pillars, equipment foundations) and of the foundations and anchoring systems of the lines pillars.
- Maintaining the proper functioning condition of AC installations in relay cabins, batteries and telecommunication cameras.
- Maintaining the proper functioning condition of the cooling systems of the transformer units.
- Snow removal of roads and access routes in substations.
  Prevention and preparedness measures as features:
- Fuel insurance for Diesel Groups.
- Backup supply insurance with Diesel Generators, UPSs and batteries.
- Proper equipment with fire extinguishers in substations.
- Providing disinfectant materials, masks and gloves for employees.
  Prevention and preparedness measures as trainings and courses:
- Staff training on fire prevention and extinguishing in electrical installations.
- Staff training on the risks of cybersecurity breaches.
- Professional training of operational staff.
  Other prevention and preparedness measures:
- Staff information and education programmes on national programmes to combat the pandemic.
- Vaccination programmes for staff.
- Measuring the temperature of employees.

- Individualization of the employee work schedule (work in shifts or with delayed schedule, teleworking programmes).
- Periodic ventilation, sanitation and disinfection of work spaces.
- Limitations on access to the command rooms of dispatcher control centers and remote control centers and, respectively, to the command rooms of PTG substations.

2.1.5. Mitigation and restoration measures

Response and restoration measures regarding the staff:
- Instructions charts.
- Insurance of technical intervention staff.
- Insurance of auxiliary intervention staff (financial, commercial, logistics).
- Insurance of operative staff and intervention and technical staff (use of management staff or semi-qualified staff or with similar qualifications to ensure continuity, reduction of the number of shifts, extension of the work schedule, etc.).
Response and restoration measures regarding the need for materials and machinery:
- Insurance of intervention/reserve pillars and accessories for lines (insulators, clamps, conductors).
- Provisional insurance of underground power lines.
- Insurance of mobile cells.
- Insurance of equipment (electric equipment) from safety/intervention stock.
- Elaboration of standard quotations for intervention works (replacements of equipment, pillars, transformation units) and assessment of a medium time of replacement/remediation.
- Insurance for Diesel groups.
- Insurance for batteries and UPS.
- Fuel reserves insurance (for diesel groups)
- Oil and SF6 gas reserves insurance.
- Winter material insurance (clothing, food, etc.)
- Fleet insurance.
Other response and restoration measures:
- Insurance of redundant/independent lines of communication (fail-safe).
- Providing spaces with special facilities (accommodation, food, sanitation, medical and psychological services) that allow the protection of staff with essential attributions for the functioning of the NPS.
- Conventions with companies specialized in construction works in the electrical field.
- Conventions with companies that own machinery for intervention.

2.1.6. The entity responsible for declaring the crisis

According to the National Disaster Risk Management Plan in Romania, the National Emergency Management System contains the following components:

- emergency committees;
- The Department for Emergency Situations;
- The General Inspectorate for Emergency Situations;
- professional emergency services and voluntary emergency services;
- operative centers and intervention coordination and management centers;
- emergency operative centers;
- commander of action/intervention.

In the event of a crisis situation, the following entities within the Ministry of Energy shall act:

- The Ministerial Committee for Emergency Situations, respectively
- The Ministerial Operative Center, and – as a part of The Ministerial Operative Center – The National Operative Center in the Energy Sector.

The entity responsible for declaring the crisis situation is *The National Operative Center in the Energy Sector.*

The following are part of The National Operative Center in the Energy Sector structure:

- Representative of the Ministry of Energy – President;
- President of the Transelectrica S.A. (TSO) Directorate;
- President of the Hidroelectrica S.A. Directorate;
- President of the Nuclearelectrica S.A. Directorate;
- Director of the Transgaz S.A.;
- Director of Power plants Bucharest S.A.;
- Director of OMV Petrom S.A.;
- President of the Oltenia Energy Complex S.A. Directorate;
- President of the Hunedoara Energy Complex S.A. Directorate;
- President of the Romania Electricity Distribution S.A. Directorate;
- President of the Oltenia Electricity Distribution S.A. Directorate;
- President of the E – Distribution S.A. Directorate;
- Director of DelgazaGrid S.A. - Director of UNO DEN;
- Director of the Energy Sector Risk Management and Prevention Department of the Ministry of Energy;
- Director of the Competent Authority for Ensuring Electricity Supply, within the Ministry of Energy.

The roles and responsibilities of The National Operative Center in the Energy Sector structure:

- it assesses the crisis situation;
- it is the entity responsible for declaring /ending a crisis;
- it ensures the implementation and coordination of the measures contained in the Risk Preparedness Plan (RPP);
- it interacts with other entities of crisis management organized at national level; - provides support to other national agencies/national departments/ministries;

- it ensures coordination for the provision of assistance and necessary resources (materials, machinery and work staff) at national level;
- it allocates the necessary resources for restoration actions;
- it allocates the necessary financial resources for restoration actions;
- provides the information office with information on the development of events and measures taken in energy crisis situations.

Other Operative Centers at the level of Entities within the NPS (the Operative Work Center in the Energy Sector):

- Representative from the administrative management; Manager/director of the operation and maintenance department;
- The manager of the Department for Emergency Situations;
- The manager of the Department of labor protection;

The roles and responsibilities of the Operative Work Center in the Energy Sector:

- it ensures the implementation of the measures decided by the National Operative Center in the Energy Sector in the affected areas with priority on the safety and health of staff, minimizing the damage caused to the assets in the NPS, as well as on the environment and other goods;
- provides support for intervention staff in case of fires or security incidents;
- it ensures the evacuation of non-essential (technical or non-technical) staff from the affected areas; - ensures communication points;
- it reports to the National Operative Center in the Energy Sector all relevant information related to the measures taken and requests assistance/support if necessary;
- it ensures the recording/preservation of necessary information to be used in the post-factum analysis of the causes that led to the occurrence of the crisis situation and the measures taken;
- provides coordination with local authorities to ensure medical needs, public order.

2.1.7. The main stages of action in case of a crisis situation

- declaration of crisis situation;
- information/announcement of crisis situation;
- assessment of the situation and risks;
- identification of necessary resources (human, material and machinery);
- adopting a response strategy according to the Risk Prevention Plan;
- implementation of the response strategy;
- field analysis of the effects of the crisis;
- post incident analysis and establishment of measures for prevention in the future;
- ending the crisis.

1. Appropriate mechanisms for information flows

The management of the crisis situation depends to a very large extent on the quality of the information received (their fairness and promptness) by the deciding

factors. In this respect, the information received must have as its source direct on-the-spot observations reported by qualified staff.

The information shall be immediately reported to the National Operative Center in the Energy Sector (directly, or through the Operative Work Center in the Energy Sector).

Depending on the crisis situation, the National Operative Center in the Energy Sector will take the following measures:

- it will issue a *Pre-Alert* briefing: providing information on the possible occurrence of a crisis situation;

- it will issue an *Alert* notification: informing that although the crisis situation is not imminent, elements have appeared that have worsened/aggravated the previous state;

- it will issue a *Danger* notification: informing that the crisis is imminent and the responsible factors must take the necessary measures to minimize the damage/losses that will be caused by the crisis situation.

- declaration of the *Crisis* situation.

For information and coordination of actions, the following command centers will be used:

- National operative center at the level of the Central Energy Dispatch;
- Local operative centers at the level of Territorial Energy Dispatchers;
- Local operative centers at the level of Territorial Units within Transelectrica S.A.;
- Local operative centers at the level of Energy Distribution Dispatchers;
- Local operative centers at the Regional Unit level within the Distribution Operators;
- Local operative centers at the level of Energy Dispatchers of Production Units.

- Local operative centers at the level of Energy Dispatchers of Large Consumption Units.

Through these command centers, all relevant information will be transmitted, regarding:

- the state and operating mode of the NPS;
- measures ordered by the National Operative Center in the Energy Sector;
- implementation mode of the actions/measures ordered by National Operative Center in the Energy Sector;
- aspects of the crisis situation.

All information available in the territory shall be centralized at the central command center (at the level of the Central Energy Dispatch) which shall carry out the National Operative Center in the Energy Sector information.

Informing the public opinion, the mass media will be centralized through a press officer designated by the National Operative Center in the Energy Sector.

At the time of the onset of the crisis, the Operative Work Center in the Energy Sector organizes intervention teams including key staff, teams that will act in the following directions:

- *Operational:*
➢ identifies potential hazards that may arise and acts to eliminate them;
➢ takes the measures of safe disconnection/withdrawal from operation of damaged equipment;
➢ takes measures to stop production units safely (if necessary);
➢ takes measures arranged according to the events and the peculiarities of the crisis situation.
- *Maintenance:*
➢ intervenes to repair equipment failures;
➢ identifies potential hazards that may arise and act to eliminate them;
➢ takes measures arranged according to the events and the peculiarities of the crisis situation. o Security
➢ restricts access to non-essential staff;
➢ ensures access for essential staff;
➢ ensures access to vehicles for evacuation or for ambulances.
- *Administrative:*
➢ provides assistance for rescue and transport operations to first aid centers or medical centers;
➢ ensures records of staff actively participating in the crisis;
➢ takes measures arranged according to the events and the peculiarities of the crisis situation.
- *Labor protection:*
➢ ensures the necessary measures in terms of labor protection;
➢ provides assistance for measuring gas emissions/concentrations;
➢ identifies and collects evidence, information related to labor protection aspects necessary for post incident analysis/investigation;
➢ takes measures arranged according to the events and the peculiarities of the crisis situation.
- *Occupational medicine:*
➢ ensures rapid access and intervention of medical staff for providing first aid;
➢ ensures the delivery of medical assistance;
➢ requests specialized medical assistance;
➢ takes measures arranged according to the events and the peculiarities of the crisis situation.
- *Firefighting:*
➢ intervenes rapidly to identify and extinguish fires;
➢ requests the intervention of the fire teams within the Emergency Situations Inspectorate;
➢ evacuates staff from fire areas;
➢ takes measures arranged according to the events and the peculiarities of the crisis situation.
- *Transport:*
➢ ensures the availability of the entire fleet for intervention and evacuation actions;

➢ ensures the presence of specialized staff at the site of the incident to ensure intervention in case of minor malfunctions to the intervention vehicles, ambulances, etc.;

➢ provides fuel supply to vehicles, machinery, Diesel Groups;

➢ provides assistance in organizing transport conditions;

➢ takes measures arranged according to the events and the peculiarities of the crisis situation. o communications;

➢ ensures the functionality of the communication network;

➢ intervenes in order to repair the failures occurring in the communication equipment;

➢ takes measures arranged according to the events and the peculiarities of the crisis situation.

- *Communications:*

➢ ensures the functionality of the communication network;

➢ intervenes in order to repair the failures occurring in the communication equipment;

➢ takes measures arranged according to the events and the peculiarities of the crisis situation.

Essential staff, criteria for determining it:

The heads of each organizational unit within the NPS entities shall establish the key staff in crisis management. The following categories of essential staff will be identified:

- technical and non-technical management staff;
- operational staff (operative management, operative service, maintenance);
- communications staff;
- maintenance staff;
- staff for supply;
- staff to ensure the transport and handling of materials;
- staff responsible for emergency situations;
- staff responsible for labor protection;
- staff responsible for occupational medicine and occupational health;
- external communication staff.

2.2. Regional and bilateral procedures and measures

2.2.1. Agreed mechanisms to cooperate within the region

Ensuring coordination before and during the electricity crisis Regional Coordination Centers (RCCs) currently provide a set of mandatory services for all TSOs to which they are affiliated, in accordance with EU legislation such as: [6,7]

- establishing common grid models;
- coordinated security analysis;
- coordinated capacity calculation;
- coordination of the decommissioning programme;

- short-term adequacy forecast;
- support for the coordination of defense and restoration plans;

In addition to the above, the RCC "TSCNET" works with TSOs and other RCCs on an early warning system to identify and mitigate potentially critical grid situations (CGS).

Starting with 2010, the EAS (ENTSO-E Awareness System) software platform was developed at the ENTSO-E level, which offers all partner TSOs a real-time global picture of the European transmission grid, a better understanding of the problem, in case of an emergency situation, of some disturbances.

The EAS platform provides the opportunity for TSOs to:
- develop the ability to assess the type and size of a disturbance;
- make the decision to act or not, without aggravating the state of the system;
- coordinate measures to solve problems related to consumption/production/power grid and system restoration;
- option to cooperate with other TSOs.

Throughout the crisis situation, the European information platform EAS (ENTSO-E Awareness Systems) will be used, the ENTSO-E and the Regional Coordination Centers will be informed and the coordinated measures established by them according to the procedures, regulations and international agreements in force will be taken.

Thus, the crisis situation is managed in collaboration and coordination with all TSOs in the region, through entities within the ENTSO-E and the Regional Security Coordination Centers, applying the dedicated procedures in force (Critical Grid Situation Procedure, coordination on Short Term Adequacy, and monitoring of frequency and cross-border exchanges by Regional Coordination and Monitoring Centers organized within AMPRION – Germany and SwissGrid – Switzerland).

2.2.2. Regional and bilateral action measures in the event of a crisis

- announcement of the crisis situation at ENTSO-E level;
- urgent communication and consultation with counterpart entities at regional and/or bilateral level to analyze the effects caused by the crisis situation;
- synchronization at bilateral /regional level with the purpose of implementing the response strategy;
- acting in the sense given by the strategy to manage and eliminate the crisis. Other measures:
- improving the adequacy indicators of the power systems in the region with the help of the shared power reserve and the additional reserve available at the interface with neighboring regions, as well as establishing the maximum quantities of electricity to be delivered at regional or bilateral level;
- improving security of supply (SoS) by eliminating congestion;
- substantial increase in net interconnection capacity;
- post incident analysis and establishment of measures for prevention in the future.

The trigger for assistance:

- major disturbances in the NPS in a certain part of the country, and the Tranmission System does not have the capacity to support the deficit from one area to another;
- difficulties arise in ensuring the adequacy of the NPS as a result of unscheduled outages of production capacities;
- trigger elements specific to risk scenarios with regional effects appear;
- the restoration activity of the neighboring power system requires this.

2.2.3. Mutual aid agreements to cooperate and coordinate actions before and during the energy crisis

Within the region of which Romania is part, the following bilateral operational agreements are in force:
- Mutual Aid Convention (Agreement on Provision of Mutual Emergency Energy Assistance for Ensuring the Reliable Operation of Power Systems of Bulgaria and Romania) that provides for the granting of a quantity of electricity between the two countries for the purpose of helping one of the countries in crisis.
- Mutual Aid Convention (Agreement on Provision of Mutual Emergency Energy Assistance for Ensuring the Reliable Operation of Power Systems of Serbia and Romania) that provides for the granting of a quantity of electricity for the purpose of helping one of the countries in crisis.
- Mutual Aid Convention (Agreement on Provision of Mutual Emergency Energy Assistance for Ensuring the Reliable Operation of Power Systems of Ukraine and Romania) that provides for the granting of a quantity of electricity for the purpose of helping one of the countries in crisis.
- Exploitation Convention (Operational Agreement) concluded between the TSOs of Romania and Serbia provides for the granting, as appropriate, of aid in the framework of the NPS restoration actions, through the 400 kV OHL Iron Gates - Djerdap interconnection line.
- Exploitation Convention (Operational Agreement) concluded between the TSOs of Romania and Bulgaria provides for the granting, as appropriate, of aid in the framework of the NPS restoration actions, through the interconnecting lines between the two countries.
- Exploitation Convention (Operational Agreement) concluded between the TSOs of Romania and Hungary provides that, as far as possible, support shall be given to restoring the neighbouring system by maintaining the voltage on the interconnecting lines and providing a quantity of electricity through the lines between the two countries [8], [9].

3. CONCLUSIONS

1. Crises are multi-dimensional: technical, economic and political
Electricity crises (shortages, blackouts, price spikes) rarely arise from a single cause. They result from interacting technical failures, market design weaknesses, fuel or supply shocks, and governance failures. Effective management therefore requires

cross-sector diagnosis and integrated responses rather than siloed technical fixes. Implication: Crisis teams must include grid engineers, market operators, fuel/logistics experts, legal advisers and political decision-makers.

2. Preparedness matters more than ad-hoc response

Systems with established contingency plans, clear operational triggers, and pre-agreed emergency procurement/shortage allocation rules recover faster and incur lower economic and social costs than those that improvise. Implication: National and regional plans should codify threshold metrics, roles, and quick-action procurement channels before crises occur.

3. Robust real-time data and situational awareness are indispensable

High-granularity, near-real-time data on demand, generation, interconnector flows and reserve margins enables precise, proportionate interventions. Lack of transparent data increases risk of overreaction and public distrust. Implication: Invest in telemetry, interoperable data platforms and transparent dashboards shared across jurisdictions.

4. Market design must allow for crisis instruments without undermining long-term signals

Markets that rigidly prioritize short-term price signals can struggle to secure capacity and fuel resilience. Conversely, heavy-handed price caps or bans can deter investment. Well-designed capacity mechanisms, reliability options, and demand-response contracts can bridge short-term reliability and long-term investment. Implication: Deploy temporary crisis instruments (e.g., scarcity pricing, bilateral reliability contracts) while protecting investor confidence through clear sunset clauses and compensation frameworks.

5. Demand-side resources are cost-effective and underutilized

Demand response, targeted conservation, and demand-flexibility (industrial interruptibility, smart appliances) reduce peak stress more quickly and cheaply than building generation. Implication: Prioritize incentives and legal frameworks for rapid demand reductions, including pre-agreed compensation for curtailed consumers.

6. Regional integration increases resilience but requires coordinated governance

Cross-border interconnectors and regional markets smooth local shocks and share reserves, lowering overall costs. However, benefits materialize only if operational rules, cost allocation and emergency coordination are harmonized. Implication: Strengthen regional institutions (TSO coordination, contingency sharing agreements) and create binding rules for emergency cross-border flows and compensations.

7. Bilateral agreements fill gaps where multilateral coordination is slow

Between neighboring states with strong trade links, bilateral emergency supply and assistance agreements (fuel swaps, emergency reserve sharing, back-up generation dispatch) can be faster and politically simpler than larger multilateral arrangements. Implication: Negotiate bilateral memoranda of understanding that specify triggers, modalities, payment terms and liability for emergency transfers.

8. Social equity and communication shape legitimacy

Crisis measures that ignore vulnerable populations (low-income households, critical health facilities) or that lack clear, consistent communication provoke non-compliance and political backlash. Implication: Embed social protection (priority supply for critical services, targeted subsidies) and a transparent public communication strategy into crisis plans.

9. Institutional clarity reduces delay and blame-shifting

Where responsibilities for procurement, rationing, and emergency declaration are fragmented, decision-making stalls. Clear authority lines (who declares emergency, who can order load shedding, who controls emergency procurement) are essential. Implication: Legislate decision authorities and fast-track procurement powers, with parliamentary/oversight review after the fact.

10. Flexible financing and contingency funding are necessary

Crisis responses require rapid spending (fuel imports, emergency generation hires, compensation). Budgetary rigidity can delay action or transfer costs in destructive ways. Implication: Maintain contingency finance lines, pre-approved credit arrangements with clear accountability rules.

11. Legal and contractual clarity prevents costly disputes

Ambiguous contracts (PPAs, interconnector usage rights) generate litigation during stress, delaying relief. Pre-agreed force-majeure, scarcity pricing rules and dispute-resolution fast-tracks reduce uncertainty. Implication: Standardize emergency clauses and dispute escalation timelines in key contracts.

12. Energy security and climate policy must be reconciled, not treated as trade-offs

Short-term energy security responses (e.g., temporary fossil fuel use) can coexist with long-term decarbonization if governed by transparent, time-limited measures and accompanied by accelerated clean investments. Implication: Approve temporary emergency fuel measures with explicit sunset clauses and parallel commitments to accelerate renewables, storage and grid upgrades.

13. Technology matters – but institutions decide outcomes

Grid hardware (storage, smart inverters, microgrids) expands options, yet without institutional frameworks (market rules, operator training, regulatory support) technology adoption will not translate into crisis resilience. Implication: Pair technical investments with regulatory reforms and operator capacity building.

14. Simulation, drills and after-action reviews are cost-effective

Tabletop exercises and full-scale drills reveal procedural gaps and boundary issues between national and regional actors. Systematic after-action reviews convert lessons into concrete reforms. Implication: Mandate periodic simulations across agencies and neighboring jurisdictions; publish transparent post-crisis reviews with accountability and reform timelines.

15. Monitoring and metrics: adopt outcome-focused KPIs

Measure preparedness and response using standard metrics: unserved energy (MWh), outage duration per customer, time-to-restore, economic cost per MWh unserved, proportion of critical services maintained, and equity indicators. Implication: Use these KPIs for benchmarking across regions and to justify investments.

16. Research gaps and future agenda

Key empirical and modelling gaps remain: optimal mix of regional vs bilateral reserves; cost-effective allocation of demand-response across socioeconomic groups; legal templates for rapid cross-border aid; behavioral responses to conservation appeals; and quantifying climate-extreme impacts on combined generation-fuel-transmission failures. Implication: Prioritize interdisciplinary research funding and data-sharing protocols to fill these gaps.

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PRACTICAL ASPECTS REGARDING THE DESIGN AND MANUFACTURING OF SINGLE-PHASE POWER TRANSFORMERS AND AUDIO-FREQUENCY TRANSFORMERS

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Abstract: The paper presents a practical methodology for designing low-power transformers, covering all essential aspects from power calculation to winding and core dimensioning. Emphasis is placed on technical accuracy, efficiency considerations, and ensuring the proper fit of windings within the transformer core, making this guide suitable for both network and audio-frequency transformers.

Keywords: Electromagnetic induction, turn ratio, magnetic core, winding, lamination.

1. INTRODUCTION

Transformers are circuit elements based on the phenomenon of electromagnetic induction, designed to transfer electromagnetic energy at a voltage V_1 and current I_1 from a primary circuit to deliver it at a voltage V_2 and current I_2 to another circuit, called the secondary [6], [9], [12], [16]. It is important to note that transformers are not sources of energy or power, even if the voltages or currents obtained in the secondary can reach values hundreds or thousands of times higher than those in the primary circuit [17], [19]. The energy extracted from the primary circuit (connected to the power supply) is found in the secondary circuit at approximately 95–98%, the difference being lost as core and winding conductor losses. An increase in voltage in one coil compared to the other coil is always achieved at the expense of the current, which decreases roughly in the same ratio, and vice versa [1], [4], [11], [14], [18].

The efficiency (or performance) of the transformer depends on numerous factors, including the quality and geometry of the iron core, the shape and dimensions of the windings, and the diameter of the winding conductors used. In low-power mains

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transformers, the most commonly used magnetic cores are E+I laminations made of cold-rolled silicon steel, which provide an electromagnetic energy transfer efficiency η between 0.95 and 0.98 [8], [10], [21].

Based on the phenomenon of electromagnetic induction, transformers can operate only with alternating current. When the frequency of the voltage applied to the primary winding is low (tens or hundreds of Hz), the secondary voltage has the same waveform and frequency. As the frequency of the voltage applied to the primary winding increases, the ferromagnetic material of the transformer core increasingly resists its magnetization and demagnetization cycle, resulting in a gradual decrease in efficiency.

If a mixture of voltages with different amplitudes and frequencies is applied to the primary winding terminals (as in the output of an audio-frequency amplifier), the secondary signal will be distorted due to the reduced high-frequency transfer efficiency. This highlights the importance of the quality of the transformer's core material. For transformers designed to operate at higher frequencies (including audio-frequency transformers, where high efficiency and compact size are desired), cores are made of permalloy or other high-quality ferromagnetic materials [15], [20], [23].

This paper will present a practical and simplified method for calculating low-power mains transformers and audio-frequency adapting transformers. The calculation steps include determining the rated power, the parameters of the laminated ferromagnetic core, the number of turns of each transformer winding, and the diameters of the winding conductors for each coil.

2. POWER CALCULATION

To quantitatively express the fundamental law of transformers, let us denote by V_1, I_1, N_1, the rated voltage, rated current, and number of turns of the primary winding, and by V_2, I_2, N_2, the rated voltage, rated current, and number of turns of the secondary winding (Figure 1). The transformer's turns ratio k_T is then defined as:

$$k_T = \frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{1}$$

The rated power of a transformer is defined as the product of the rated voltage and rated current of the primary winding:

$$P = V_1 \cdot I_1 \tag{2}$$

If losses are neglected, the power S is fully transferred to the secondary circuit and can be expressed by the equation:

$$P = V_2 \cdot I_2 \tag{3}$$

From equations (2) and (3) it follows:

$$V_1 \cdot I_1 = V_2 \cdot I_2, \text{ or } \frac{V_1}{V_2} = \frac{I_2}{I_1} = k_T \tag{4}$$

The first step that must be precisely determined before constructing a transformer is its intended purpose. This requires knowing the maximum voltage and current values of the secondary winding, V_2 and I_2. We will consider three common practical cases:
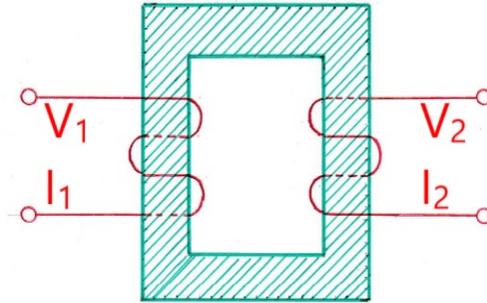
Fig.1. Transformer with a single secondary winding

a) single secondary winding (Figure 1). If there is a single secondary winding delivering the maximum voltage V_2 and maximum current I_2, the power of the secondary will be:

$$P_2 = V_2 \cdot I_2 \tag{5}$$

b) Multiple separate secondary windings (Figure 2, a). If there are multiple secondary windings that must operate independently, delivering maximum voltages V_2^1, V_2^2,..., V_2^n and maximum currents I_2^1, I_2^2,..., I_2^n, the total secondary power is calculated by summing the powers of each secondary winding individually:

$$P_2 = P_2^1 + P_2^2 + \ldots + P_2^n = V_2^1 \cdot I_2^1 + V_2^2 \cdot I_2^2 + \ldots + V_2^n \cdot I_2^n \tag{6}$$

a)   b)
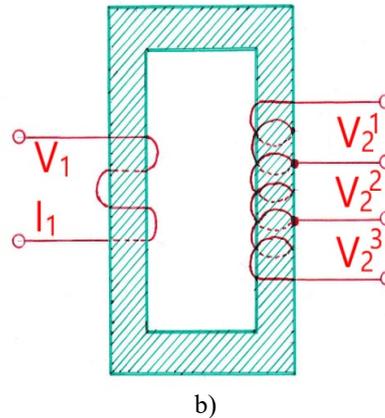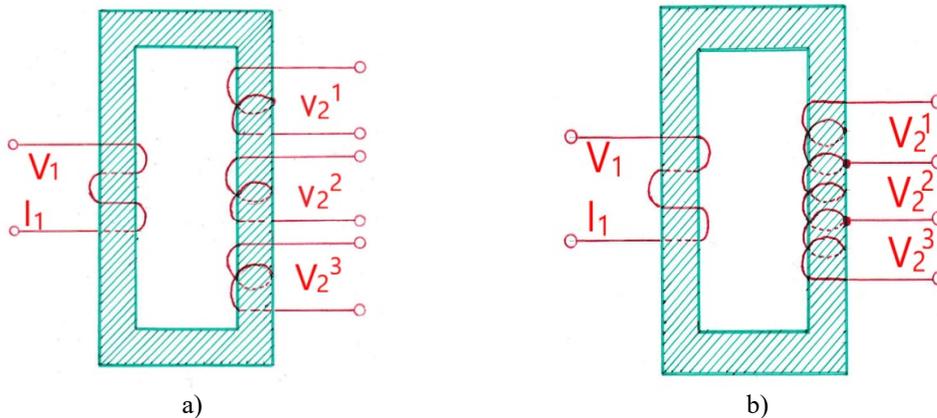
Fig.2. Transformer: a) with multiple separate secondary windings; b) with single secondary winding with multiple taps

Example: If the secondary has one winding of 230 V / 2 A and another winding of 120 V / 4 A, the total power is: $P_2 = 230 \cdot 2 + 120 \cdot 4 = 460$ VA + 480 VA = 940 VA.

In practice, there are situations where not all secondary windings need to supply electric energy simultaneously [16], [22].

Knowing this operating mode is important because it can lead to a reduction in the transformer size and, consequently, manufacturing costs. Returning to the example above and assuming that the 230 V and 120 V voltages are used alternately, never simultaneously, the transformer power can be considered as the largest power among the two windings, i.e., 480 VA.

    c) Single secondary winding with multiple taps (Figure 2, b). In this case, the secondary power is calculated based on the maximum voltage of the entire winding and the current that must be delivered, using equation (5). Here, the maximum voltage will be the sum of the voltages between the winding ends and the intermediate taps, while the maximum current will be the same through all sections, which are connected in series.

After calculating the rated power P_2 of the secondary winding, the rated power of the primary winding P_1 can be determined, considering the transformer efficiency, which ranges between 0.95 and 0.98:

$$\eta = \frac{P_2}{P_1} = 0{,}95...0{,}98 \tag{7}$$

from wich it follows:

$$P_1 = \frac{P_2}{0{,}95...0{,}98} = (1{,}02...1{,}05) \cdot P_2 \tag{8}$$

3. CALCULATION OF THE MAGNETIC CORE CROSS-SECTION

As previously mentioned, for low-power transformers, the magnetic cores are most often constructed using E + I laminations (Figure 3). A review of the technical literature shows that these laminations are further classified according to certain dimensional characteristics, with catalogs available to facilitate the correct selection of lamination types and the transformer design.

Regarding the lamination stack, two essential characteristics must be known: the core cross-section and the window dimensions. At this stage, it is assumed that the material of the laminations is already known (silicon steel sheet, hot- or cold-rolled). The cross-section s of the magnetic core is obtained by multiplying the thickness c of the lamination stack by the width b of the central limb of the E-lamination, expressed in centimeters (Figure 4). The resulting cross-section is expressed in square centimeters.

Knowing the cross-section is mandatory because the maximum power P transferred from the primary winding to the secondary winding depends directly on the core cross-section [9], [24].
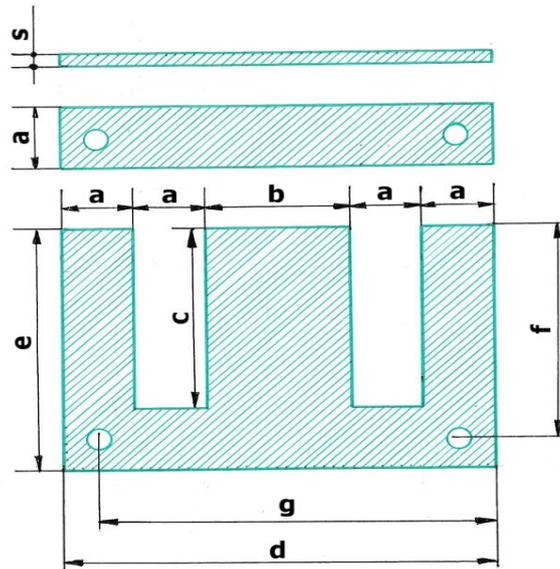
Fig.3. E + I -type lamination

For high-quality ferromagnetic materials (e.g., cold-rolled silicon steel), this relationship is expressed by the equation:

$$s = \sqrt{P} \tag{9}$$

When the magnetic core is made from lower-quality laminations, such as plain iron or annealed steel, a proportionality factor greater than 1 is introduced in the equation (9), typically ranging between 1,1 and 1,6:

$$s = (1,1\ldots1,6) \cdot \sqrt{P} \tag{10}$$

The other essential characteristic of the magnetic core is the window, which represents the empty space inside the lamination stack after assembly, located between the central limb and one of the side limbs. In E + I laminations, there are two equal windows, one on each side of the central limb. These empty windows accommodate the transformer casing, which houses the primary and secondary windings. The window dimensions are considered after completing the winding calculations (number of turns and conductor diameters) to verify that the designed windings physically fit within the casing and the window space.

Once the minimum required cross-section of the magnetic core is established using equations (8) or (9), the corresponding lamination stack is selected. Special attention must be paid to ensure that the chosen core cross-section is never smaller than the calculated value. Conversely, a much larger cross-section than required ensures proper transformer operation but results in a larger physical size and higher conductor consumption, increasing manufacturing costs. If the difference between the transformer rating and the total load connected to the secondary winding is significant, the

transformer may operate with a lower power factor due to the increased proportion of reactive power in the total apparent power.
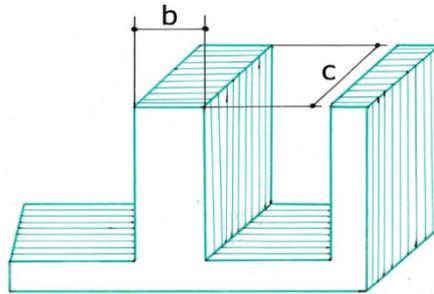
Fig. 4. E-laminations stack

Adjustment of the cross-section can be easily achieved by increasing or decreasing the stack thickness (i.e., the number of laminations used). In practice, it is advisable, as far as reasonably possible, for the cross-section b·c to be square, i.e., b=c. By adhering to this criterion, the length of each turn is minimized, since among all rectangles with a given area s, the square has the smallest perimeter. This reduces conductor length, lowers the winding's electrical resistance, and consequently decreases energy losses due to voltage drop.

4. CALCULATION OF WINDINGS

As previously demonstrated, the ratio of voltages in the primary and secondary windings is equal to the ratio of the number of turns of these windings- equation (1). At first glance, one might deduce that, to achieve a voltage transformation from V_1 to V_2, any pair of values for the number of turns N_1 and N_2 could be chosen, as long as their ratio satisfies this equation. In reality, this is entirely incorrect because a specific number of turns cannot handle any arbitrary voltage. For a given number of turns, there is a maximum voltage that can be transformed efficiently while ensuring safe operation. This limitation is imposed by the magnetization conditions of the transformer core (the magnetic flux density depends on the number of turns of the primary winding, the current flowing through it, and the size and quality of the magnetic core) [13].

Based on accumulated practical experience in designing and operating transformers, a simple and precise empirical relationship has been established for determining the number of turns per volt:

$$N_{turns/V} = \frac{55}{s} \tag{11}$$

where s is the magnetic core cross-section, and 55 is a constant dependent on network frequency and core quality. This constant can take the value 50 for high-quality silicon steel laminations and may increase up to 60 for lower-quality magnetic materials such as ordinary iron sheets [5].

Knowing the number of turns per volt for the selected core, the number of turns for the transformer windings can be calculated:

$$N_1 = U_1 \cdot N_{turns/V}; \; N_2 = U_2 \cdot N_{turns/V} \tag{12}$$

When the secondary coil contains multiple separate windings, this calculation is applied individually for each voltage.

Example: A transformer with a magnetic core cross-section of 5 cm² requires windings with $N_{turns/V} = \dfrac{55}{5} = 11$ turns per volt. For a secondary winding that must deliver 24 V, the number of turns is calculated as $N_2 = 24 \cdot 11 = 264$ turns.

5. SIZING OF WINDING CONDUCTORS

The next step in the calculation consists of determining the minimum diameters for the winding conductors. To achieve this, the maximum currents in the primary and secondary windings must first be determined, using the following equations:

$$I_1 = \frac{P_1}{V_1} \quad I_2 = \frac{P_2}{V_2} \tag{13}$$

Example: If the supply voltage of the primary winding is $V_1 = 230$ V and the maximum power of the primary, determined from previous calculations, is $P_1 = 200$VA, then the current in the primary winding is: $I_1 = \dfrac{200}{230} = 0,87$ A, approximately 0,9 A.

It is known that when an electric current flows through a conductor, part of the applied voltage is lost due to the conductor's electrical resistance. Physically, this loss appears as heat because of the Joule effect. This voltage drop also implies a loss of power, directly proportional to the conductor's resistance and the square of the current flowing through it ($P = R \cdot I^2$).

Table 1. **Winding calculation data**

d (mm)	s (mm²)	I_{max} (mA)			n_s (turns/cm²)		n_1 (turns / cm)
		j= 2A/ mm²	j= 2,5A/ mm²	j= 3A/ mm²	without insulation between layers	with insulation between layers	
0,15	0,01707	35,3	44,2	53	2880	2260	55
0,18	0,02545	51	63,7	76,5	2050	1730	47,5
0,2	0,03142	62,9	78,6	94,8	1715	1465	43,4
0,22	0,03801	75	95	114	1460	1210	39,2
0,25	0,04909	98	123	147	1140	978	35

0,28	0,06158	122	151	185	925	813	31,5
0,3	0,07069	141	177	212	807	722	29,6
0,35	0,09621	192	240	289	594	530	25,3
0,4	0,126	252	315	378	470	350	22,5
0,45	0,159	318	398	477	371	277	19,9
0,5	0,196	392	490	590	300	234	18,1
0,55	0,2376	475	594	713	246	190	16,4
0,6	0,2827	566	707	848	209	162	15,1
0,65	0,3312	662	888	993	180	142	14,1
0,7	0,3848	770	960	1150	153	125	13,1
0,75	0,442	882	1110	1331	134	110	12,3
0,8	0,503	1000	1256	1510	127	95,5	11,4
0,85	0,569	1140	1420	1700	106	87	11
0,9	0,636	1270	1590	1910	93	78	10,2
0,95	0,710	1420	1775	2130	84	70	9,8
1	0,785	1570	1960	2360	75	65	9,3
1,2	1,131	2260	2730	3400	52	40,5	7,7
1,4	1,54	3080	3850	4620	39	30,7	6,7
1,5	1,767	3530	4420	5300	33,5	26,5	6,2

To keep voltage drops in the windings within acceptable limits, the electrical resistances of these conductors must be as low as possible, especially when higher currents are involved. The resistance R of a conductor is directly proportional to its length l and the resistivity ρ of the material, and inversely proportional to its cross-section s:

$$R = \rho \cdot \frac{l}{s} \tag{14}$$

In transformer windings, the lengths are well defined, the number of turns is precisely calculated, and the length of a turn is dictated by the magnetic core cross-section. The resistivity of winding conductors (usually copper) is well known. Therefore, the only variable that can be adjusted to reduce winding resistance is the conductor's cross-section s.

In practice, the minimum cross-section of the winding conductor (and thus the minimum diameter) for a given current is determined using the current density j. For small transformers, a current density of 2...2,5 A/mm^2 is generally accepted for copper. Higher values (3...4 A/mm^2) may be used in cases such as:

- Secondary windings with a small number of turns in transformers installed outdoors, benefiting from natural or forced ventilation;
- Transformers with intermittent operation, with short periods of load alternating with rest periods.

Given a current density j, the conductor cross-section s in mm^2 is calculated as:

$$s = \frac{I}{j} \tag{15}$$

where I is the maximum current in the winding (A). The calculated section of
the wire is considered the minimum, and the result is always rounded up to the nearest
standardized conductor size.

Example: For a maximum winding current of 1 A and a current density
$j=2.5$ A/mm², the conductor cross-section is $s=0.4$ mm². Knowing that manufacturers
provide conductor diameters without insulation, the conductor diameter d is:

$$s = \frac{\pi \cdot d^2}{4} = 0{,}785 \cdot d^2 \tag{16}$$

The inverse equation can be written:

$$d = \sqrt{\frac{4 \cdot s}{\pi}} \approx 1{,}13\sqrt{s} \tag{17}$$

Returning to the stated example, the diameter of the conductor with a cross-
section of 0,4 mm² will be $d \approx 1{,}13\sqrt{0{,}4} = 0{,}714$ mm. The immediately higher
standardized diameter for this value is 0,75 mm, which is the value that will be chosen
for making the coil.

To eliminate the extensive calculations required by the preceding equations,
tabulated data are commonly employed in practice, providing the main winding
parameters for each standardized conductor diameter. By combining equations (15) and
(17), a direct correlation is established between the maximum allowable current I (A)
and the minimum diameter of the uninsulated winding conductor d (mm):

$$d = 1{,}13\sqrt{\frac{I}{j}} \tag{18}$$

In equation (18), the current density j is taken in A/mm², and for value $j = 2$
A/mm², often used in practice, , the wire diameter can be calculated using the
approximative formula:

$$d \approx 0{,}8 \sqrt{I} \tag{19}$$

If the required diameter is not available, the winding can be made using two or
more smaller conductors in parallel, ensuring that the sum of their diameters without
insulation is at least equal to the minimum diameter calculated [1].

Based on the calculation performed, Table 1 was prepared, from which the
windings data can be directly extracted.

6. DETERMINING THE SPACE OCCUPIED BY WINDINGS

The next step in designing the transformer is an approximate calculation of the
total space occupied by the transformer windings. Neglecting this step may have
unpleasant consequences, as there is a risk that the windings will not fit on the core.

The total space occupied by the windings practically represents the area of the winding's cross-section. To calculate this approximately, all winding data must be known in advance: total number of turns, conductor diameters, and type of insulation between layers and windings. Therefore, the choice of the core package and, implicitly, the casing is made only after the winding calculations are completed, because a given core package may have a sufficient power rating but a window that is too small for the designed windings [3].

Until now, we have used the conductor diameter without insulation. From this point forward, the insulated conductor diameter, denoted d_{is}, is considered. Key notions here are turns/cm and turns/cm².

To determine how many turns of a given conductor fit in 1 cm of length (column n_1 in Table 1), proceed as follows: wrap 20 turns of the conductor as tightly as possible around a pencil with a circular section, without gaps. Measure the winding length L in mm. The number of turns/cm n_1 is calculated proportionally:

$$20 \text{ turns}.......L \text{ (mm)}$$
$$n_1 \text{ turns}.......10 \text{ (mm)}$$

from which:

$$n_1 \text{ (turns/cm)} = \frac{200}{L} \tag{20}$$

The choice of 20 turns is arbitrary for ease of calculation and more precise measurement of L. If the conductor is very thin, 30–40 or more turns may be used.

If a micrometer is not available, the insulated conductor diameter can also be determined proportionally:

$$20 \text{ turns}.........L \text{ (mm)}$$
$$1 \text{ turn}..........d_{is} \text{ (mm)}$$

from which:

$$d_{is} \text{ (turns/cm)} = \frac{L}{20} \tag{21}$$

The cross-sectional area s_{is} of a conductor with diameter d_{is} can be approximately calculated as:

$$s_{is} \approx 0{,}8 \cdot d_{is}^2 \tag{22}$$

To calculate the total space occupied by the windings, proceed as follows:
- multiply the number of turns of each winding by the conductor's cross-section s_{is};
- sum the results for all transformer windings; the final result represents the effective total cross-sectional area occupied by the conductors;

- to account approximately for space losses due to turn shape, insulation between layers, and uneven winding, multiply the result by a factor between 2 and 3. The resulting value approximates the minimum window area of the magnetic core, expressed in mm².

Example: A transformer has four windings with the following numbers of turns and conductor diameters:
- N_1 = 1430 turns, d_{is} = 0,44 mm;
- N_2 = 4000 turns, d_{is} = 0,2 mm;
- N_3 = 35 turns, d_{is} = 0,98 mm;
- N_4 = 45 turns, d_{is} = 0,8 mm.

The magnetic core is an E+I lamination package with a window area of 5 cm x 2,5 cm = 12,5 cm² = 1250 mm² and we aim to determine wether the 4 transformer's windingss will fit within the mentioned window.Calculating the space occupied:
- Winding 1: $0{,}8 \cdot 0{,}44^2 \cdot 1430 = 250$ mm²;
- Winding 2: $0{,}8 \cdot 0{,}2^2 \cdot 4000 = 128$ mm²;
- Winding 3: $0{,}8 \cdot 0{,}98^2 \cdot 35 = 27$ mm²;
- Winding 4: $0{,}8 \cdot 0{,}8^2 \cdot 45 = 23$ mm².

Total cross-sectional area is: 250 + 128 + 27 + 23 = 428 mm², which is nearly three times smaller than the core window area. Therefore, the four windings fit comfortably in the chosen magnetic core.

7. DIMENSIONS OF E+I LAMINATIONS

In general, technical literature indicates a transformer core by the type of lamination (E6, E10, etc.) and the stack thickness. To deduce the relevant dimensions, it is necessary to know certain dimensional correlations. For this study, refer again to Figure 4 from Chapter 3 of this work, which shows the notations used for different dimensions of E+I laminations. The number following the letter E when specifying the lamination type represents the dimension a in Figure 4, expressed in millimeters. There are precise relationships between the dimensions a, b, c, d, e, f and g (for example, b=2a, d=6a, etc.). Numerical values of these dimensions in millimeters for several commonly used laminations are shown in Table 2. The column indicating the weight of a lamination is subdivided according to the lamination thickness s (0.35 mm or 0.5 mm) [2].

Using the notations from Figure 4, the core window area can be calculated as:Using the notations from Figure 4, the core window area can be calculated as:

$$s_{window} = a \cdot 3a \cdot 10^{-2} = 0{,}03 \cdot a^2$$

The factor 10^{-2} accounts for the fact that the dimension a is expressed in millimeters. For example, an E8 lamination (a=8 mm) has a window area: $0{,}03 \cdot 8^2 = 2{,}4$ cm².

If h denotes the thickness (or height) of the lamination stack in millimeters, the cross-sectional area of the magnetic core is calculated as:

$$s_{core} = h \cdot 2a \cdot 10^{-2} = 0{,}02 \cdot h \cdot a$$

Table 2. **Dimensions and weight of some common types of E + I laminations**

Dimensions (mm)							Weight (g)	
a	b=2a	c=3a	d=6a	e=4a	f=3,5a	g=5a	s=0,35	s=0,5
5	10	15	30	20	-	-	1,2 0,4	1,7 0,57
6,4	12,8	19,2	38,4	25,6	-	-	2,07 0,66	3,04 0,97
8	16	24	48	32	-	-	3,08 1,03	4,53 1,59
10	20	30	60	40	35	50	4,95 1,61	7,1 2,36
12,5	25	37,5	75	50	43,75	62,5	7,28 2,52	10,7 3,7
14	28	42	84	56	49	70	9,4 3,16	13 4,63
16	32	48	96	64	56	80	12,4 4,14	18 6,21
18	36	54	108	72	63	90	15,6 5,2	23 7,6
20	40	60	120	80	70	100	24,3 6,4	28,3 9,4
25	50	75	150	100	87,5	125	30 10,5	44 14,5
32	64	96	192	128	112	160	50 16,5	73 23,6

Returning to the E8 lamination example, a stack of E8 laminations with thickness h=10 mm has a core cross-section of: $10 \cdot 8 \cdot 0,02 = 1,6$ cm^2.

8. CALCULATION OF AUDIO FREQUENCY ADAPTER TRANSFORMERS

Audio frequency adapter transformers belong to the category of special transformers. Unlike mains transformers, which serve as the connection element between two power networks with different voltages, audio frequency transformers are used in public address systems, with the main role of matching the output impedance of the audio power amplifier stage with the transmission line impedance of the audio signal to the system's loudspeakers [11].

Public address systems are sound reinforcement installations designed for use in public spaces frequented by a wide audience and consist of audio equipment such as speakers, microphones, mixers, audio signal sources, public announcement generators, and so on.

The most common public address systems include:

- radio-distribution networks, through which a program transmitted by a radio station is delivered via subscriber lines simultaneously to a variable number of special speakers, called radio-distribution speakers, located at individual subscribers' residences;

- radio-amplification systems, which transmit radio programs, music, announcements, etc., to crowded spaces such as classrooms in educational institutions, airports, train stations, bus terminals, shopping centers, and similar locations [7].

The audio signals handled and transformed by audio frequency transformers fall within the audio frequency spectrum, ranging from 20 Hz to 20 kHz. Typically, an audio frequency adapter transformer operates within a much narrower signal frequency range, between 100 Hz and 12 kHz. This limitation occurs because, as the audio signal frequency increases, the transformer's magnetic core increasingly opposes the very rapid magnetization-demagnetization cycles. This phenomenon can be mitigated by constructing the magnetic core from high-quality magnetic alloy laminations (for example, permalloy).

For audio adaptation transformers, the method and calculation formulas used to determine the core and winding parameters differ somewhat from those for mains transformers [12].

The rated power of a step-up audio adapter transformer, which receives the signal at its primary from the output of the final amplification stage, is determined using the relation:

$$P = P_{sp} \cdot n_{sp} \tag{23}$$

where:
- P_{sp} is the rated power of a subscriber's speaker;
- n_{sp} is the total number of speakers connected to the radio-distribution / radio-amplification network.

The next step is to determine the output voltage of the amplifier's final audio unit, V_g:

$$V_g = \sqrt{P \cdot Z_a} \tag{24}$$

where:
- P is the rated power of the audio amplifier in watts (W);
- Z_a is the output impedance of the audio amplifier in ohms (Ω), measured at a frequency of 1000 Hz.

Knowing the audio output voltage V_g and the nominal voltage of the transformer secondary, which is equal to the audio line voltage V_{al} indicated on the technical data plates of the speakers, the transformation ratio of the transformer k_T can be calculated:

$$k_T = 1{,}1 \cdot \frac{V_{al}}{V_g} \tag{25}$$

where 1.1 is a correction factor that accounts for power losses in the secondary winding relative to the primary winding.

The cross-section sss of the transformer's magnetic core is determined using the equation:

$$s = 16 \cdot \sqrt{\frac{P}{f_j}} \tag{26}$$

where f_j is the lower limit of the audio signal frequency in the transformer's secondary. In the absence of other information, f_j is taken as 100 Hz.

Considering a magnetic induction $B \leq 5000$ Gs, the number of turns per volt for the transformer windings, $n_{turns/V}$ is determined using the formula:

$$n_{sp/V} = \frac{10^8}{4{,}44 \cdot f_j \cdot B \cdot Sfe} \tag{27}$$

Knowing the turns per volt, the number of turns of the primary winding n_1 can be calculated, as well as the number of turns n_2 of the secondary winding:

$$n_1 = n_{turns/V} \cdot V_g \tag{28}$$

$$n_2 = n_1 \cdot k_T \tag{29}$$

The next step is determining the conductor diameters for the transformer windings. First, the maximum primary current I_1 is determined:

$$I_1 = \sqrt{\frac{P}{Z_a}} \tag{30}$$

The diameter d_1 of the primary winding conductor is:

$$d_1 = 0{,}65 \cdot \sqrt{I_1} \tag{31}$$

The diameter d_2 of the secondary winding conductor is:

$$d_2 = \frac{d_1}{\sqrt{k_T}} \tag{32}$$

9. CONCLUSIONS

Based on the theoretical analysis and the presented calculation relations, it is confirmed that the sizing and design of transformers depend directly on the electrical operating conditions for which they are intended. Thus, although power transformers and audio-frequency matching transformers belong to the same family of electromagnetic devices, they employ distinct calculation methodologies in order to correctly satisfy the requirements of their specific applications.

In the case of the single-phase power network transformer, its use at the supply network frequency (also called "industrial frequency") of 50 Hz requires that the proper transfer of power from the primary winding to the secondary winding is the main requirement for its operation. A judicious correlation between the rated power of the

secondary winding and the rated power of the load is the premise for operation under a power factor as close as possible to its limit value (cosφ = 0.9) established by the Order no. 76 of November 2, 2016 of the National Energy Regulatory Authority.

For audio-frequency matching transformers used in public address networks and sound distribution systems, the primary concern is not power transfer itself, but the correct impedance matching between the output unit of the power amplifier and the transmission line driving the distributed loudspeakers. The role of the turns ratio and spectral characteristics in maintaining audio signal fidelity is emphasized, along with the need to use high-quality magnetic materials in order to limit losses at higher frequencies within the audio spectrum.

The obtained calculation results confirm that core sizing, determination of the number of turns, selection of conductor cross-sections, and correlation with the level of magnetic induction must be approached integratively to simultaneously achieve efficiency, thermal stability, and distortion-free operation. The accuracy of these steps is essential for the reliability of the transformer and for the optimal operation of the electronic or electrotechnical system in which it is integrated.

In conclusion, the design of transformers — regardless of their application category — remains a multidisciplinary process in which knowledge of electromagnetism, electrical engineering, electronics, and material science must be rigorously combined. The precise application of calculation relations ensures the development of high-performance, energy-efficient, and operationally stable equipment capable of meeting the technical, economic, and safety requirements imposed by modern applications.

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A VIRTUAL INSTRUMENT FOR TEMPERATURE MONITORING THROUGH THE USE OF INTEGRATED SENSORS

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Abstract: The automatic or autonomous control of a process involves the monitoring of its parameters and their regulation in order to adapt their values relative to those predefined by the user. In this paper, the control of the environment in which the process takes place is assumed, and the monitored parameter is the temperature of this environment. Temperature values are acquired using an integrated temperature transducer from the LM9402x series, whose operation is based on the effect of temperature variations on the electrical characteristics of the p–n junction. In order to ensure the autonomy of the monitoring system with respect to the process control system, a hardware structure variant based on the widely adopted open-source Arduino platform is proposed. Although the programming software associated with this platform is based on a standard C++ compiler, in this work LabVIEW programming is employed so as to enable integration into a hierarchical virtual instrument for monitoring the entire process.

Key words: temperature, integrated sensors, Arduino, LabVIEW.

1. GENERAL CONSIDERATIONS ON TEMPERATURE MEASUREMENT

In order to measure temperatures, it is necessary to define a precise scale with stable and reproducible values, between which interpolation relationships can be established, and which should be as close as possible to the thermodynamic temperature scale derived from the laws of thermodynamics. Currently, the International Practical Temperature Scale of 1968 (IPTS-68) is used, which establishes that the unit of temperature is the Kelvin [K], equal to 1/273.16 of the thermodynamic temperature corresponding to the triple point of water.

In practice, tolerated units of measurement are also used, namely: the degree Celsius (t [°C]), the degree Fahrenheit (t [°F]), and the degree Rankine (t [°R]) [1].

The principles used in the construction of temperature transducers are: resistive, thermoelectric, semiconductor conduction, optical, or piezoelectric.

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Regardless of the principle used, a thermal contact between the sensing element and the environment or object being measured is required. Such a contact is considered perfect when there is no longer a thermal gradient between the sensing element and the medium or object. Achieving such contact requires a certain amount of time necessary to reach thermal equilibrium, which is a slow process [2], [3], [4].

The amount of heat exchanged per unit time between the sensing element, at an instantaneous temperature T, and the measured environment, is given by:

$$dQ = a \cdot A \cdot (T_I - T) \cdot dt \tag{1}$$

where a represents the thermal conductivity and A the contact surface area.

Considering the specific heat c of the sensing element and its mass m, the amount of heat absorbed by it is:

$$dQ = m \cdot c \cdot dT \tag{2}$$

Assuming that heat losses during transfer are negligible, based on relations (1) and (1), one may write:

$$a \cdot A \cdot (T_I - T) \cdot dt = m \cdot c \cdot dt \tag{3}$$

Introducing the thermal time constant, $\tau_T = (m \cdot c)/(a \cdot A)$ the solution of the differential equation (3) is obtained as:

$$T = T_I - k \cdot e^{-\frac{t}{\tau_T}} \tag{4}$$

The graph of the temperature response based on solution (4) is presented in fig.1.a. In obtaining this response, the amount of heat released or absorbed by the sensing element—through which it modifies the initial measured temperature from T_I to T_2—was not taken into account. Thus, the measured medium or object was approximated by an ideal model represented by an infinite heat source.

Taking into account the influence of the sensing element on the measured quantity, represented by the temperature variation ΔT, in practice one does not measure the actual temperature T_I, but its modified value T_2 (fig.1.b).
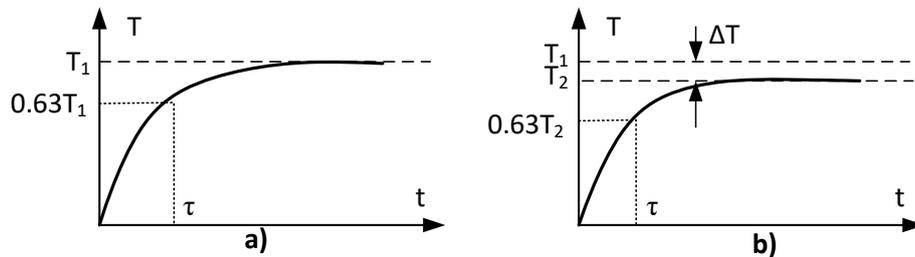

Fig.1. Temperature response of the sensor

Theoretically, an infinite time is required to achieve thermal equilibrium between the sensing element and the environment (object), but for sufficiently good accuracy this time may be considered to be 0.5–1 min [5], [6], [7].

2. INTEGRATED TEMPERATURE SENSOR LM94021

The LM94021 is a CMOS-based integrated temperature sensor that incorporates both the sensing element and the signal conditioning circuitry, providing a precise analog output voltage dependent on the temperature of the device package.

The sensor operates over a wide temperature range from −50 °C to +150 °C and generates an output voltage inversely proportional to the measured temperature. It is powered by a single-supply voltage starting at 1.5 V. Due to its low power consumption, the LM94021 is well suited for battery-powered systems as well as for general-purpose temperature monitoring applications.

The sensitivity of the sensor can be configured via two logic inputs, Gain Select 1 (GS1) and Gain Select 0 (GS0). These inputs allow the selection of the voltage-to-temperature transfer ratio, as summarized in Table 1.

Table 1. **Sensitivity configuration of the LM94021 sensor**

GS1	GS0	Sensitivity (mV/°C)
0	0	−5.5
0	1	−8.2
1	0	−10.9
1	1	−13.6

The gain selection inputs are compatible with TTL logic levels, enabling dynamic gain optimization during operation or facilitating system diagnostics.

The transfer characteristics of the LM94021 sensor are illustrated in Figure 2.a, while the recommended application circuit is shown in Figure 2.b.
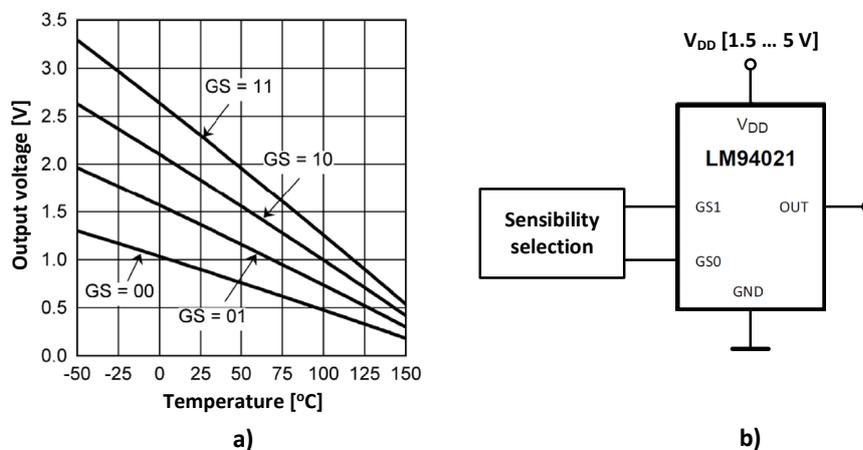

Fig.2. Integrated temperature sensor LM94021

The electrical characteristics corresponding to supply voltages in the range of 1.5 V to 5.5 V are provided in Table 2.

Table 2. **Sensitivity configuration of the LM94021 sensor**

PARAMETER		CONDITIONS	TYPICAL [1]	LIMITS [2]	UNITS (LIMIT)
	Sensor Gain	GS1 = 0, GS0 = 0 GS1 = 0, GS1 = 1 GS1 = 1, GS0 = 0 GS1 = 1, GS0 = 1	−5.5 −8.2 −10.9 −13.6		mV/°C mV/°C mV/°C mV/°C
	Load Regulation [3]	Source ≤ 2.0 µA [4] Sink ≤ 100 µA Sink = 50 µA	 0.4	−1 1.6	mV (max) mV (max) mV
	Line Regulation [5]	(V_{DD} - V_{OUT}) ≥ 200 mV	200		µV/V
I_S	Supply Current	T_A = +30°C to +150°C T_A = −50°C to +150°C	9	12 13	µA (max) µA (max)
C_L	Output Load Capacitance		1100		pF (max)
	Power-on Time [6]	C_L= 0 pF C_L=1100 pF	0.7 0.8	1.6 2.4	ms (max) ms (max)
V_{IH}	GS1 and GS0 Input Logic "1" Threshold Voltage			V_{DD}- 0.5V	V (min)
V_{IL}	GS1 and GS0 Input Logic "0" Threshold Voltage			0.5	V (max)
I_{IH}	Logic "1" Input Current [7]		0.001	1	µA (max)
I_{IL}	Logic "0" Input Current [7]		0.001	1	µA (max)

Although the LM94021 exhibits good linearity over its operating range, its response is not perfectly linear, displaying a slightly parabolic behavior. Nevertheless, the transfer characteristics can be considered approximately linear for most practical applications.

For higher accuracy, the manufacturer provides tabulated output voltage values (in millivolts) for all four selectable sensitivities across the entire temperature range. These data can be implemented using a look-up table approach in sensor-based applications. The complete transfer tables are available from the manufacturer's official documentation.

The values in this table can also be determined analytically based on the expressions defined for the 4 sensitivities as follows:

1. For GS1=0 and GS2=0

$$V_{TEMP}[mV]=870,6mV-5,506\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)-0,00176\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)^2 \quad (5)$$

2. For GS1=0 and GS2=1

$$V_{TEMP}[mV]=1324,0mV-8,194\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)-0,00262\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)^2 \quad (6)$$

3. For GS1=1 and GS2=0

$$V_{TEMP}[mV]=1777,3mV-10,888\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)-0,00347\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)^2 \quad (7)$$

4. For GS1=1 and GS2=1

$$V_{TEMP}\,[mV]=2230,8mV-13,582\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)-0,00433\frac{mV}{^oC}\cdot\left(T\text{-}30^oC\right)^2 \quad (8)$$

Additionally, the transfer characteristics may be analytically approximated using sensitivity-specific expressions corresponding to each GS1/GS0 configuration. For linear approximation within a limited temperature interval, two reference points are selected from the transfer table, and the sensor response is modeled using a first-order linear equation.

Let $(T_1,\ V_1)$ and $(T_2,\ V_2)$ denote the lower and upper reference points, respectively. The linear approximation between these points is defined by a standard interpolation relationship, represented by (9).

$$V\text{-}V_1=\left(\frac{V_2\text{-}V_1}{T_2\text{-}T_1}\right)\cdot\left(T\text{-}T_1\right) \quad (9)$$

where
- ✓ T_1 [ºC] and V_1 [mV] are the coordinates of the lower point;
- ✓ T_2 [ºC] and V_2 [mV] are the coordinates of the upper point.

3. IMPLEMENTATION OF THE TEMPERATURE MONITORING SYSTEM

3.1. Hardware Structure

For temperature monitoring, the LM94021 sensor manufactured by Texas Instruments was tested. The sensor is mounted on the LM9402xEVM Evaluation Module (EVM), produced by the same manufacturer.
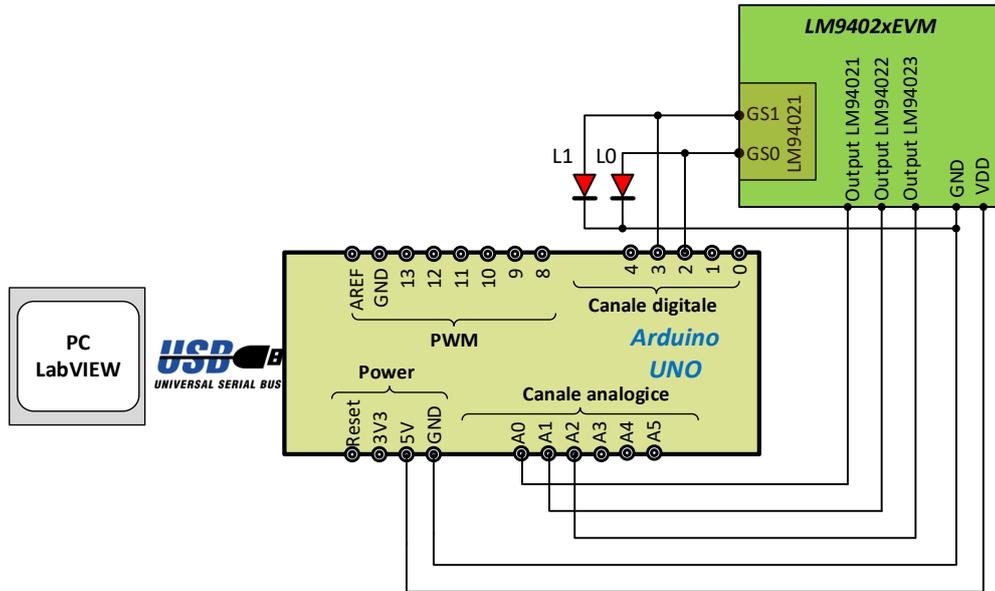

Fig.3. Block diagram of the monitoring system

Fig. 3 presents the block diagram of the monitoring system.

The temperature information, represented by the voltage at the sensor output, is acquired using the Arduino Uno module, specifically through the analog input channel AI0, to which the sensor signal is connected. Other analog quantities can be acquired using the remaining analog channels by appropriate selection.

The Arduino Uno module also performs a first stage of signal processing, namely the analog-to-digital conversion, using the converter integrated into the ATmega328 microcontroller on the Arduino Uno board.

Communication between a computer and the Arduino Uno module is achieved via the USB serial interface. Thus, the acquired data can be retrieved and further processed using an application developed in LabVIEW, which provides the information to the user in a synthetic and accessible form through an appropriate graphical interface. Through the same interface, the user can also generate commands or control signals for the monitored technical system.

Sensor sensitivity control is performed via two digital channels, allowing the user to select any of the four available sensitivity levels through the application. Two LEDs are associated with these channels and display the selected sensitivity in binary format. The use of these LEDs also demonstrates the capability of the user to generate commands or controls for the monitored technical system.

3.2. Hardware Structure

The Texas Instruments LM9402xEVM evaluation module (EVM), shown in Fig. 4, is designed to evaluate the operation and performance of the LM94021, LM94022, and LM94023 sensors [8].
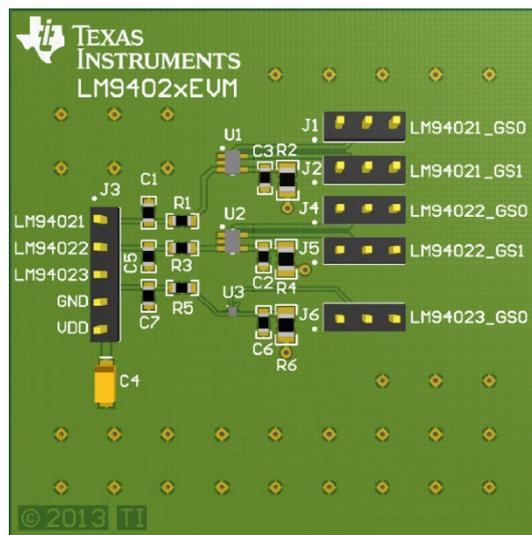

Fig.4. Texas Instruments LM9402xEVM evaluation module

The LM94021, LM94022, and LM94023 devices are precision analog-output temperature sensors implemented in integrated CMOS technology. They feature

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sensitivity selection pins that allow the user to configure the output sensitivity of the temperature–voltage transfer characteristic [9], [10].

The LM9402xEVM module includes all three analog temperature sensors, as well as the necessary jumpers for sensitivity configuration, either by connection to the supply voltage VDD (GSx = 1) or to ground GND (GSx = 0).

Sensitivity control can also be achieved using appropriate logic levels provided by the digital channels of the Arduino Uno module and applied to the same jumper terminals.

The jumpers have the following functions:

✓ J1 – Sensitivity selection terminal (GS0) for LM94021. The 0.1-inch header allows the user to set the transfer function sensitivity to HIGH (GS0 = 1) or LOW (GS0 = 0).

✓ J2 – Sensitivity selection terminal (GS1) for LM94021. The 0.1-inch header allows the user to set the transfer function sensitivity to HIGH (GS1 = 1) or LOW (GS1 = 0).

✓ J4 – Sensitivity selection terminal (GS0) for LM94022. The 0.1-inch header allows the user to set the transfer function sensitivity to HIGH (GS0 = 1) or LOW (GS0 = 0).

✓ J5 – Sensitivity selection terminal (GS1) for LM94022. The 0.1-inch header allows the user to set the transfer function sensitivity to HIGH (GS1 = 1) or LOW (GS1 = 0).

✓ J6 – Sensitivity selection terminal (GS0) for LM94023. The 0.1-inch header allows the user to set the transfer function sensitivity to HIGH (GS0 = 1) or LOW (GS0 = 0).

- J3.P1 – Analog temperature sensor output for LM94021.
- J3.P2 – Analog temperature sensor output for LM94022.
- J3.P3 – Analog temperature sensor output for LM94023.
- J3.P5 (GND) – Ground reference pin.
- J3.P6 (VDD) – Supply voltage for LM94021, LM94022, and LM94023.

The schematic diagram of the Texas Instruments LM9402xEVM evaluation module, highlighting the components used, is shown in Fig. 5.

Fig.5. Default configuration of jumpers

3.3. Virtual Instrument

The virtual instrument is a program developed in LabVIEW that manages communication with the Arduino Uno module and performs data processing for the information acquired from the sensors via the Arduino module [11], [12].

3.3.1. Front Panel of the Virtual Instrument

The front panel contains the user interface elements, which can be used for:
- ✓ data or command input (input-type elements), referred to as controls;
- ✓ display of results obtained through data processing, referred to as indicators.

Figure 6. shows screenshots of the front panel corresponding to the operation of the virtual instrument.
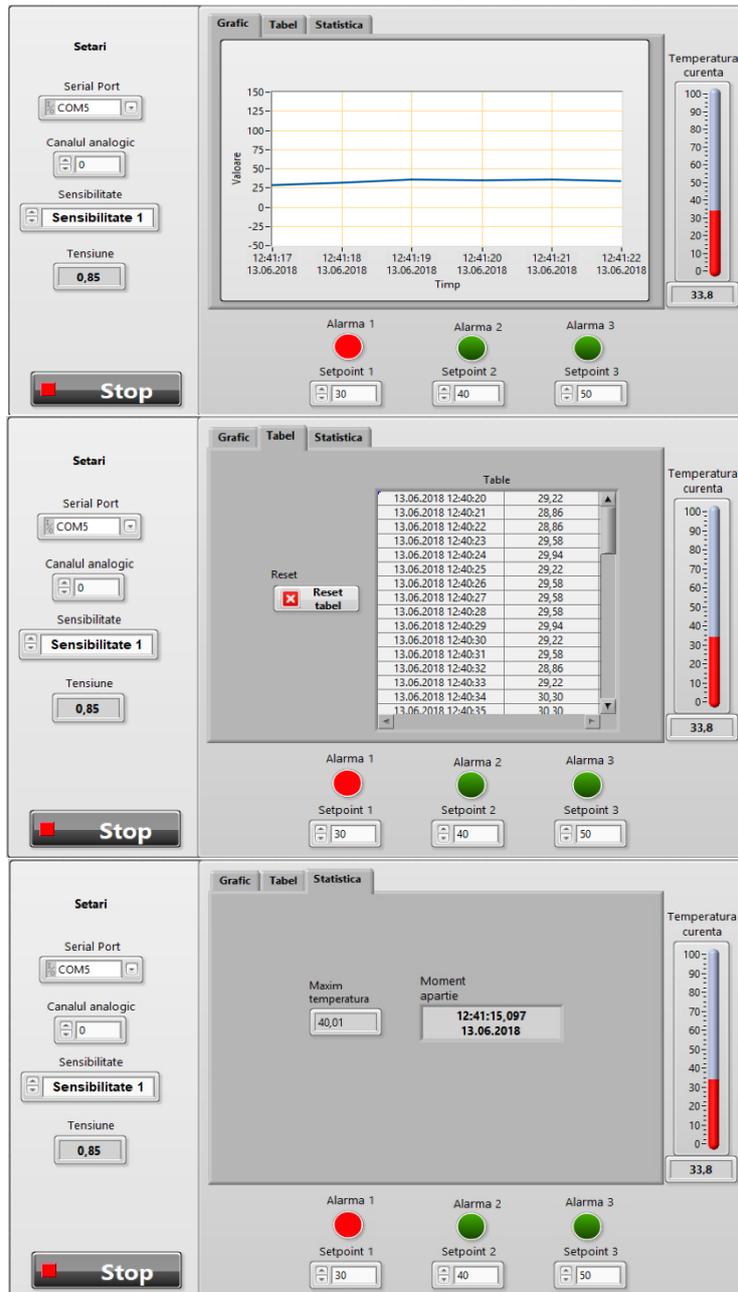

Fig.6. Front panel of the virtual instrument

In the implementation of this application, three component windows of the front panel are used, the user having the possibility to choose any of them at any time. These three windows with the names **Graph**, **Table**, **Statistics** can be selected via the Tab command.

The **Graph** window is used to display the time evolution of the monitored temperature values. The time units on the horizontal axis represent real time, including date, hour, minute, and second corresponding to each sensor reading.

The **Table** window provides a tabular representation of the temperature values and their corresponding acquisition times.

The **Statistics** window displays the maximum identified temperature value over the entire acquisition period, together with the time at which it was detected.

The front panel also includes the following indicators:

- ✓ **Voltage** – numeric indicator displaying the sensor output voltage in volts;
- ✓ **Current Temperature** – slider-type indicator displaying the current temperature value in degrees;
- ✓ **Alarm 1**, **Alarm 2**, **Alarm 3** – Boolean indicators signaling the exceedance of the configured alarm thresholds.
  The front panel controls and their defined functions are:
- ✓ **Serial Port** – ring-type control used to select the USB port to which the Arduino Uno module is connected;
- ✓ **Analog Channel** – numeric control used to select the analog input to which the sensor is connected;
- ✓ **Sensitivity** – ring-type control used to select one of the four available sensor sensitivity levels;
- ✓ **Setpoint 1**, **Setpoint 2**, **Setpoint 3** – numeric controls used to set the alarm thresholds;
- ✓ **STOP** – Boolean control used to stop program execution.

3.3.2. Block Diagram of the Virtual Instrument

The block diagram represents the program itself and consists of operations, functions, and programming structures arranged according to the data flow required for execution.

Program execution continues until the *STOP* button on the front panel is activated. This behavior is implemented by enclosing all operations and functions within a *While* structure. A delay of 1 second between consecutive cycles is introduced using the *Wait Until Next ms.vi* function, resulting in a temperature acquisition rate of one sample per second.

The *Open Serial.vi* function, which establishes serial communication with the module controlled via the *LINX* package (in this case, the Arduino Uno), and the *Close.vi* function, which terminates communication and releases system resources, are excluded from the *While loop*. These functions are executed at program start and upon activation of the *STOP button*, respectively.

LINX is a utility developed by National Instruments that enables the integration of Arduino development boards into the LabVIEW programming environment, without requiring direct embedded programming of the microcontroller. Communication between LabVIEW and the Arduino platform is typically achieved via a USB serial interface, based on a client–server architecture in which the Arduino runs *LINX* firmware, while the LabVIEW application controls system operation [14].

Through *LINX*, users can access the analog and digital input/output resources of the Arduino board, as well as certain communication interfaces, by means of dedicated Virtual Instruments (VIs) available in LabVIEW. This approach facilitates the rapid development of data acquisition, monitoring, and control applications in a graphical and intuitive manner.

The overall block diagram of the virtual instrument is shown in Figure 7.
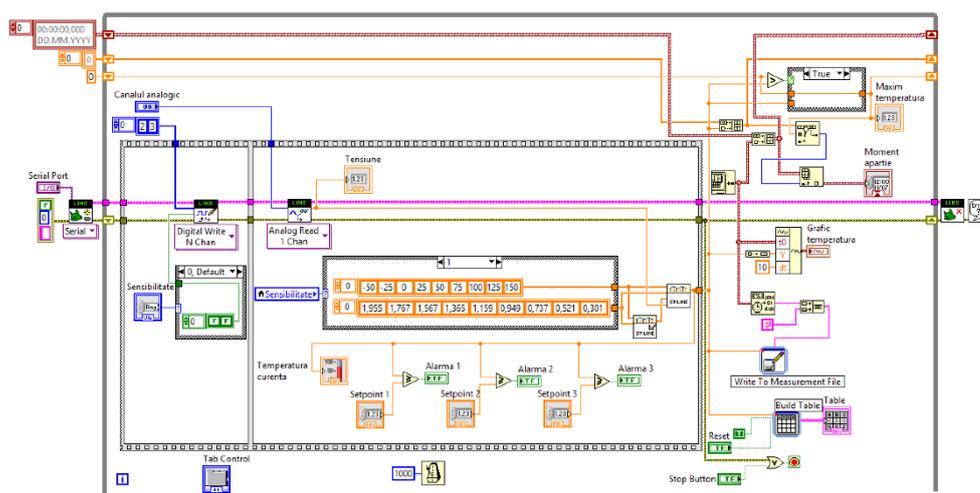
Fig.7. Block diagram of the virtual instrument

Data acquisition and processing are performed in two stages:
1. Selection of the sensitivity value;
2. Reading the sensor voltage and performing the voltage-to-temperature conversion.

This functionality is implemented using a *Sequence* structure and the *Digital Write.vi* function, which writes a Boolean value to a selected digital output, and the *Analog Read.vi* function, which reads the value available at the selected analog input. Digital outputs DIO2 and DIO3 are used to control GS0 and GS1, respectively, while the analog input is selected via the **Analog Channel control**.

The **Sensitivity control** selects one of the four required combinations according to Table 1, generated using a *CASE* structure, as shown in Figure 8.
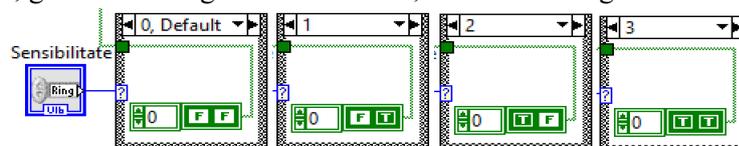
Fig.8. Sensitivity selection

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For voltage-to-temperature conversion, several approaches are possible, including the use of analytical relations or lookup tables. However, these methods either require complex implementation or significant memory allocation. To avoid these limitations while ensuring validity over the entire measurement range, an interpolation-based method was selected.

Spline interpolation is applied using a limited set of voltage–temperature pairs from the sensor datasheet for each sensitivity configuration. The Spline Interpolant.vi and *Spline Interpolation.vi* functions are used, as illustrated in Figure 9.
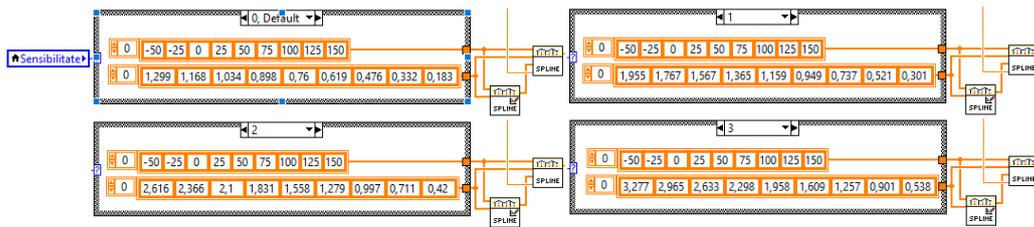
Fig. 9. Voltage-to-temperature conversion

The *Spline Interpolation.vi* function returns the interpolated temperature value corresponding to the measured voltage, based on the coefficients generated by the *Spline Interpolant.vi* function, which computes the second derivative of the spline interpolation function at the specified data points.

The obtained temperature values are compared with the alarm thresholds set using the **Setpoint 1** to **Setpoint 3** controls. When a threshold is exceeded, the corresponding LED indicators **Alarm 1** to **Alarm 3** are activated, as shown in Figure 10.
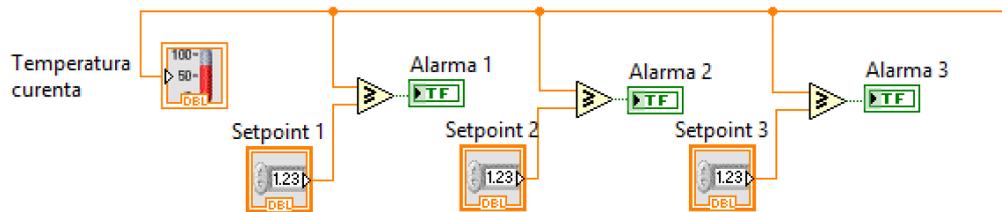
Fig.10. Alarm generation

The identification of the maximum temperature value during acquisition, as well as the time at which it occurs, is performed in each acquisition cycle using a Shift Register. This mechanism allows the comparison of the previously identified maximum with the newly acquired value and retention of the higher value.

Simultaneously, temperature values and their corresponding timestamps are stored and indexed in vectors. Using the index of the maximum temperature value, the associated acquisition time can be determined. Figure 11 highlights the portion of the virtual instrument responsible for identifying the maximum temperature value and its corresponding time.
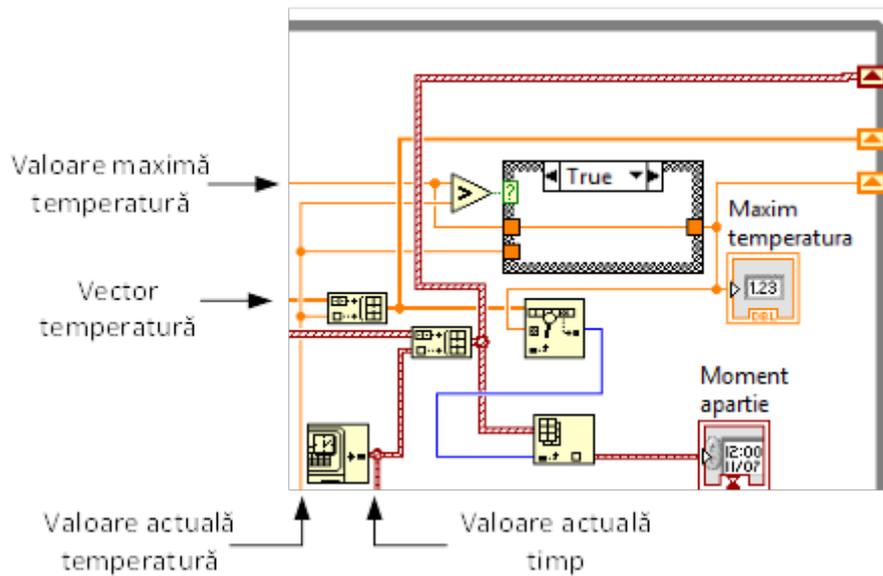
Fig. 11. Identification of the maximum temperature value

The acquired temperature values are exported in *.lvm* format to a file that can subsequently be opened in a Microsoft Excel spreadsheet and used to maintain a historical record of the measured quantities. For this purpose, the *Write to Measurement File Express VI* function is employed, as illustrated in Figure 12.
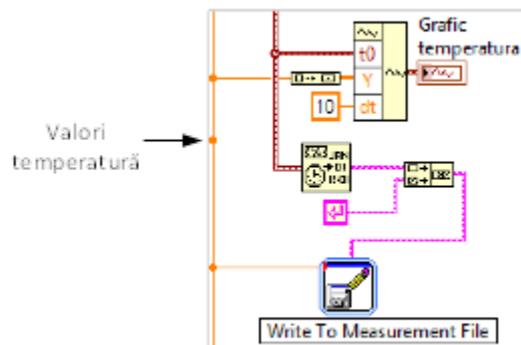
Fig. 12. Export of the acquired values

This function enables the writing of data to text-based measurement files (*.lvm*), binary measurement files (*.tdm* or *.tdms*), or Microsoft Excel files (*.xlsx*).

4. CONCLUSIONS

Temperature monitoring is important not only for obtaining information about its value, but also because many physical processes are influenced by temperature. Based on temperature-related information, it is therefore possible to derive relevant insights and to monitor and control such physical processes.

In temperature evaluation through measurement, the selection of the measuring instrument, and particularly of the sensor, is of critical importance. The sensor must reach thermal equilibrium with the surrounding environment as rapidly as possible, a process that depends on the thermal transfer properties between the environment and the sensor. Under certain conditions, the temperature of the sensor itself may generate a temperature gradient, leading to discrepancies between the measured temperature and the actual temperature of the system. This gradient increases with the mass of the sensor. In such cases, the measured temperature varies not only with the system temperature but also with the thermal transfer characteristics of the system.

The above conditions are best satisfied by sensors based on the properties of the p–n junction, as employed in the LM9402x series of temperature sensors manufactured by Texas Instruments and used in the present application.

Arduino represents a platform through which information systems capable of "perceiving" the surrounding environment via sensors and "controlling" it through actuators can be developed. This platform is open-source and consists of both a development environment and a development board based on an AVR microcontroller, which can be interfaced using virtual instrumentation applications.

Virtual instruments are employed to ensure flexibility and enhanced data processing capabilities for both software and hardware systems, particularly the personal computer, in applications designed to develop, test, or control processes and systems while performing precise measurements of both analog and digital signals. Moreover, they enable the creation of user-defined systems tailored to specific application requirements. Industries with automated processes widely employ virtual instrumentation systems to improve productivity, reliability, safety, optimization, and overall system stability.

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SMART MATERIALS IN ELECTRICAL ENGINEERING. MATHEMATICAL MODELS, SIMULATIONS AND APPLICATIONS

ILIE UȚU[1], BRANA LILIANA SAMOILĂ[2]

Abstract: This paper presents a detailed analysis of smart materials used in electrical engineering, with an emphasis on theoretical foundations, mathematical models, finite element method (FEM) numerical simulations, and industrial applications. Piezoelectric, magnetostrictive materials, and shape memory alloys are analyzed, and their advantages and limitations are discussed in comparison with conventional electromechanical systems. The results demonstrate the high potential of smart materials in modern conversion, control, and automation systems.

Keywords: smart materials, piezoelectric materials, magnetostrictive materials, FEM, electrical engineering

1. INTRODUCTION

Smart materials [1] represent a class of functional materials capable of modifying their properties in response to external stimuli such as electric and magnetic fields, temperature variations, or mechanical loads. Smart materials are also referred to as intelligent functional materials.

In electrical engineering [11], these materials enable the development of adaptive systems with high energy density, superior precision, and advanced functional integration. Compared to classical solutions, smart materials allow miniaturization and direct control of energy conversion processes.

Smart materials—also referred to as sensory, adaptive, metamorphic, multifunctional, or intelligent materials—are the result of collaboration between specialists in materials science, mechanical engineering, and civil engineering [2], [12], [18]. They can combine actuator and sensor functions within the same structure. One of the most effective methods for obtaining smart materials is particle assemblage, achieved either by attachment or by integration of active elements into a unified structure [25].

The simplest smart material structure consists of a sensor, an actuator, and a feedback amplifier. A mechanical coupling between the sensor and actuator may or may

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not exist; however, the coupled configuration is more effective because sensing and actuation occur at the same location [13], [21], [27].

The concept of smart materials originates from intelligent forms found in natural systems, namely living organisms. Consequently, smart materials are designed to perform natural functions such as sensing, actuation, control, and intelligence. Smart or intelligent materials have the ability to self-adapt to external stimuli, and their functions respond intelligently to changes in the surrounding environment [15], [20], [26].

2. CLASSIFICATION OF SMART MATERIALS

Smart materials [3] can be classified according to the type of stimulus they respond to and the type of physical response generated. The most commonly used smart materials in electrical engineering are piezoelectric materials, magnetostrictive materials, shape memory alloys, and electroactive polymers [5] [14], [24].

2.1. Piezoelectric Materials

Piezoelectric materials (such as quartz, lead zirconate titanate, ceramic materials, and piezoelectric polymers) [3] [4] generate an electric voltage when subjected to mechanical stress and, conversely, deform when exposed to an electric field.

Their main applications in electrical engineering include pressure, force, acceleration, and vibration sensors, signal generators, micro- and nano-positioning actuators, and vibration-based energy harvesting systems [16].

2.2. Electrostrictive and Magnetostrictive Materials

Electrostrictive materials exhibit deformation proportional to the square of the applied electric field and are used in applications requiring precise and stable displacement. Magnetostrictive materials exhibit spontaneous polarization and allow switching through the application of an external electric field [17], [23].

These materials are used in variable-capacitance capacitors, non-volatile memory devices, and high-precision actuators.

2.3. Shape Memory Alloys (SMA)

Shape memory materials rely on martensite–austenite phase transformations induced thermally or electrically. Applying an electric current, heats the material, causing it to return to its memorized shape. They are mainly nickel–titanium (Nitinol) or copper–zinc–aluminium alloys and are used in thermal relays, intelligent switches, and actuation elements in automated systems [19].

2.4. Smart Semiconductor Materials

Modern semiconductors can be considered smart materials due to their ability to respond to electrical, optical, or thermal stimuli.

Their main applications include temperature and light sensors, power devices (IGBT, MOSFET), control and protection circuits, and smart electrical grids.

2.5. Electrochromic Materials

Electrochromic materials change their color or transparency when subjected to an electric field.

They are used in smart displays, electrochromic windows, and status indicators in electrical equipment.

3. THEORETICAL FOUNDATIONS AND MATHEMATICAL MODELS

The behaviour of smart materials is described by coupled constitutive equations that correlate electrical, mechanical, magnetic, and thermal fields. For piezoelectric materials, linear relationships are widely used during the design phase, whereas for SMAs and magnetostrictive materials, nonlinear temperature-dependent models are required [6], [8], [22].

The mathematical models presented are generally linear or quasi-linear. In real applications, nonlinearities, hysteresis effects, and temperature- and frequency-dependent behaviour are present. Advanced modelling therefore requires numerical methods such as the finite element method (FEM) and multiphysics simulations.

3.1. Mathematical Modelling of Piezoelectric Materials

Piezoelectric constitutive equations enable bidirectional mechanical–electrical energy conversion and are essential in the design of precision transducers and actuators.

The linear behaviour of piezoelectric materials is described by the constitutive equations:

$$\begin{cases} S = s^e T + dE \\ D = dT + \varepsilon E \end{cases} \tag{1}$$

where:

S – mechanical strain vector

T – mechanical stress tensor

E – electric field intensity

D – electric displacement

s^e – elastic compliance matrix

d – piezoelectric coefficient

ε – dielectric permittivity

3.2. Modeling of Magnetostrictive Materials

Magnetostrictive strain is described by:

$$\lambda = \frac{\Delta L}{L} = k \cdot M^2 \tag{2}$$

where:

ε – relative strain
M – magnetization
k – magnetostrictive constant

The magnetic field and mechanical force are coupled through Maxwell's equations and mechanical equilibrium relationships.

3.3. Shape Memory Alloys (SMA) – Thermomechanical Model

The phase transformation is described by the martensite fraction ξ:

$$\varepsilon = \varepsilon_0 + \xi \cdot \varepsilon_L \tag{4}$$

The constitutive behaviour can be expressed in simplified form as:

$$\varepsilon = \varepsilon_0 + \xi \cdot \varepsilon_L \tag{4}$$

where:

ε_L – maximum recoverable strain
T – temperature
σ – m
echanical stress

3.4. Smart Semiconductor Materials in Electrical Engineering

The electrical conductivity of semiconductors depends on temperature and electric field:

$$\sigma(T) = q\left(n\mu_n + p\mu_p\right) \tag{5}$$

where:

q – elementary charge
n – concentration of free electrons
p – concentration of holes
μ_n – electron mobility
μ_p – hole mobility

4. FEM NUMERICAL SIMULATIONS

The finite element method (FEM) [10] is the primary numerical analysis tool for smart materials due to its ability to handle multiphysics problems. FEM simulations allow evaluation of electric, magnetic, and mechanical field distributions, as well as optimization of geometry and control parameters.

For piezoelectric actuators, simulations include electrostatic equations and mechanical equilibrium relations, while for SMAs, heat transfer equations are also incorporated. These simulations are essential for predicting dynamic behaviour and durability.

Figure 1 presents the result of a numerical simulation for a piezoelectric actuator, highlighting the near-linear relationship between applied voltage and mechanical displacement.

Figure 2 illustrates the behaviour of an actuator made from a shape memory alloy (NiTi), where deformation depends on temperature due to the martensite–austenite phase transformation.

Observations: These simulations are representative of the preliminary design phase. In real applications, models are extended using multiphysics FEM methods that include nonlinearities, hysteresis, and thermal effects.
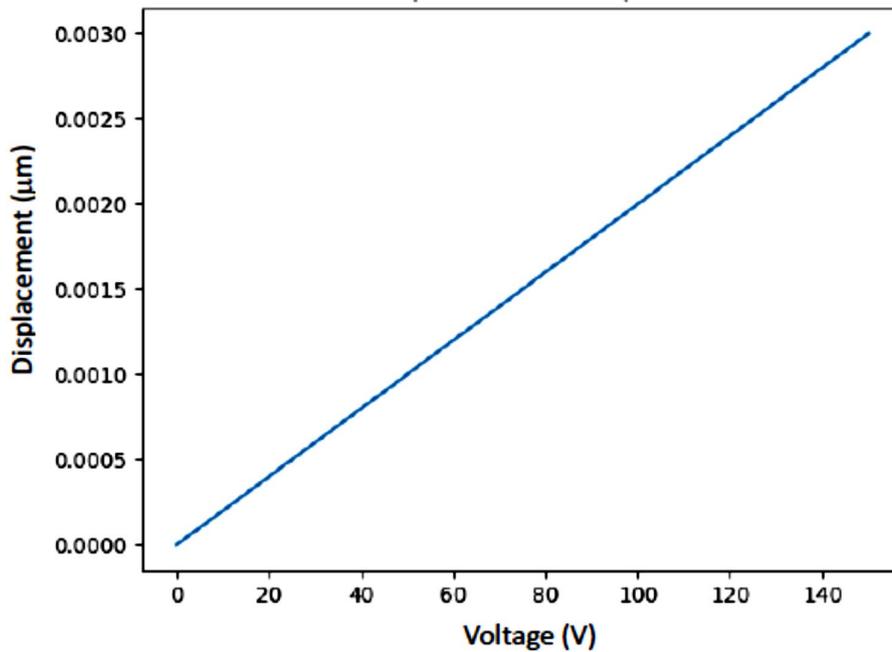
Fig.1. Piezoelectric actuator simulation – displacement versus applied voltage
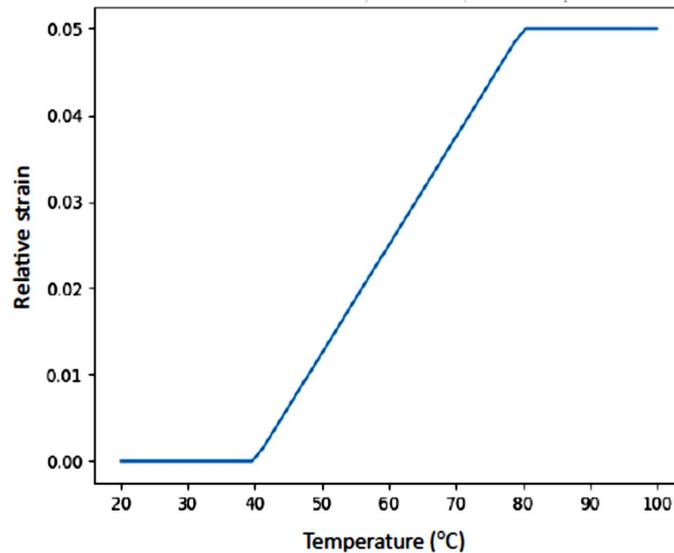
Fig.2. SMA actuator simulation – relative strain versus temperature (martensite–austenite transformation)

5. EXAMPLES OF INDUSTRIAL APPLICATIONS

Shape memory alloys are frequently used to build compact actuators and intelligent relays, demonstrating good reliability for applications with moderate duty cycles. [7]

5.1 Piezoelectric Micro-Positioning Actuators

A relevant industrial example is the use of piezoelectric actuators in micro-positioning systems for the semiconductor industry, where nanometric resolutions are achieved [9].

The miniaturization of positioning systems in semiconductor manufacturing and optics has driven the adoption of piezoelectric actuators. Linear mathematical models provide quick displacement estimates, while FEM simulations are mandatory for nonlinear analysis at high frequencies or complex electromechanical effects.

Piezoelectric actuators powered at 100–150 V provide micrometer-scale displacements with sub-1 μm accuracy in open-loop control, outperforming classical micrometric screw systems due to higher energy density and faster response.

5.2 Magnetostrictive Actuators for Vibration Control

Linear actuators based on the magnetostrictive material Terfenol-D are used in active vibration control systems for electrical turbines and generators. Although their mechanical performance is inferior to conventional hydraulic actuators, this is compensated by rapid response and direct integration with electrical systems.

Despite higher costs, their fast response and electrical integration justify their use.

6. CONCLUSIONS

This paper highlights the strategic role of smart materials in modern electrical engineering. Through mathematical modeling and FEM simulations, these materials can be effectively integrated into advanced industrial applications, contributing to the development of high-performance and energy-efficient systems.

The integration of smart materials in electrical engineering opens significant perspectives for efficient and adaptive systems. Future research focuses on multifunctional materials and advanced simulation methods.

Compared to conventional electromechanical systems, smart materials offer significant advantages such as miniaturization, high response speed, and direct integration with electrical control systems. These features are critical in applications where space and precision are essential.

However, limitations include high material costs, nonlinear behavior, temperature dependence, and the need for advanced control algorithms. In high-power applications, conventional solutions often remain more robust and cost-effective.

Current research directions focus on multifunctional materials, integration of smart materials with artificial intelligence systems, and the extension of FEM simulations toward fully multiphysics and multiscale models.

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STRUCTURAL HEALTH MONITORING FOR DANGEROUS VIBRATIONS FOR TOWERS IN SMALL CAPACITY WIND TURBINES

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Abstract: Vibration monitoring is an essential element in assessing the structural health of modern engineering systems. This paper presents a methodology for acquiring and processing vibration signals using MEMS sensors integrated into a monitoring system designed for structures subjected to dynamic loads. The measured signals are processed by digital filtering, in particular using a Butterworth filter, to reduce noise and highlight the relevant spectral components. The results obtained demonstrate the system's ability to identify variations in vibration amplitude and frequency, correlated with the occurrence of non-compliant operating conditions. The proposed methodology provides support for the implementation of predictive maintenance strategies and contributes to increasing the safety and reliability of monitored structures.

Key words: renewables, wind turbine, vibrations, sensor, damage.

1. INTRODUCTION

The oscillations of a wind turbine tower, known in the literature as **"tower sway"**, represent the dynamic phenomenon whereby the tower structure undergoes lateral and longitudinal displacements under the action of aerodynamic, gravitational and mechanical loads generated during operation. These oscillations are characteristic of a flexible system subjected to time-varying excitations and can be described by classical models of vibrations of structures with low rigidity [1], [3], [7], [10].

From a mechanical point of view, the wind turbine tower behaves like a **beam embedded at the base**, with distributed mass and a system of rigidities that depend on its geometry, material properties and rotor inertia. The oscillations are the result of the complex interaction between:

1. **The aerodynamic loads of the blades**, predominant at frequencies *1P* (one blade pass per rotation) and *3P* (the interaction of the three blades);

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2. **Centrifugal and gyroscopic forces**, which introduce additional components to changes in wind direction or rotor speed variations;
3. **The interaction between the tower, nacelle and rotor**, which form a dynamically coupled system;
4. **Atmospheric turbulence**, which causes random and nonlinear excitations.

The tower sway phenomenon occurs predominantly at low frequencies (generally between **0.1 and 1 Hz**, depending on the height and stiffness of the tower), these frequencies being specific to the fundamental vibration modes of the structure [21]. The magnitude of the oscillations depends on the wind speed, the mass-stiffness ratio, and the mass of the rotor at the top of the tower, which acts as an amplifier of dynamic effects [4], [14], [17], [20], [22].

Monitoring and controlling tower oscillations is essential for:

- **assessing the** long-term **structural integrity** of the turbine,
- **preventing resonance phenomena**, which can induce dangerous increases in vibration amplitude,
- **optimising turbine control strategies** (pitch control, yaw control, load reduction),
- **early detection of structural defects** such as material fatigue, cracks or weld degradation.

2. MEMS ACCELEROMETERS

MEMS accelerometers are motion transducers in a single IC device package. The typical construction uses a pair of capacitors with a silicon micromass with metal plates in the middle. Very thin regions of silicon suspend the mass in the middle. Changes in the position of the mass result in changes in the capacitance of the device, which translate into a voltage signal proportional to the acceleration of the suspended mass [2], [6], [9], [13].

MEMS devices require a power supply to operate, and some MEMS accelerometers have a built-in digitiser to eliminate unnecessary noise and the need to match sensors and recorders [19]. As shown in Figure 1, the frequency response of a MEMS accelerometer is like a low-pass filter with a limit at the resonance frequency.
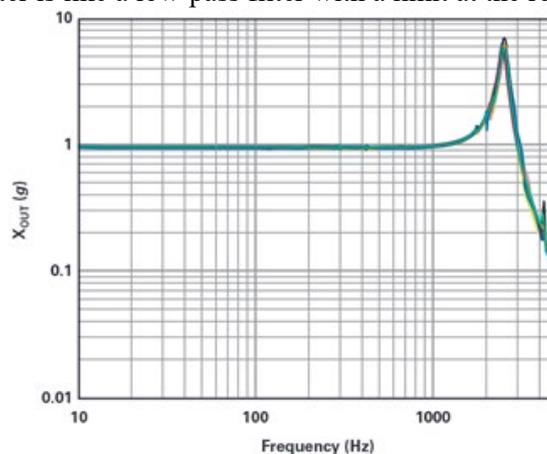
Fig.1. Frequency response of a MEMS accelerometer (ADXL354) on its X-axis.

Due to compensation displacements, MEMS accelerometers perform better at higher frequencies up to their resonance frequency.

3. THE ADXL 345 SENSOR
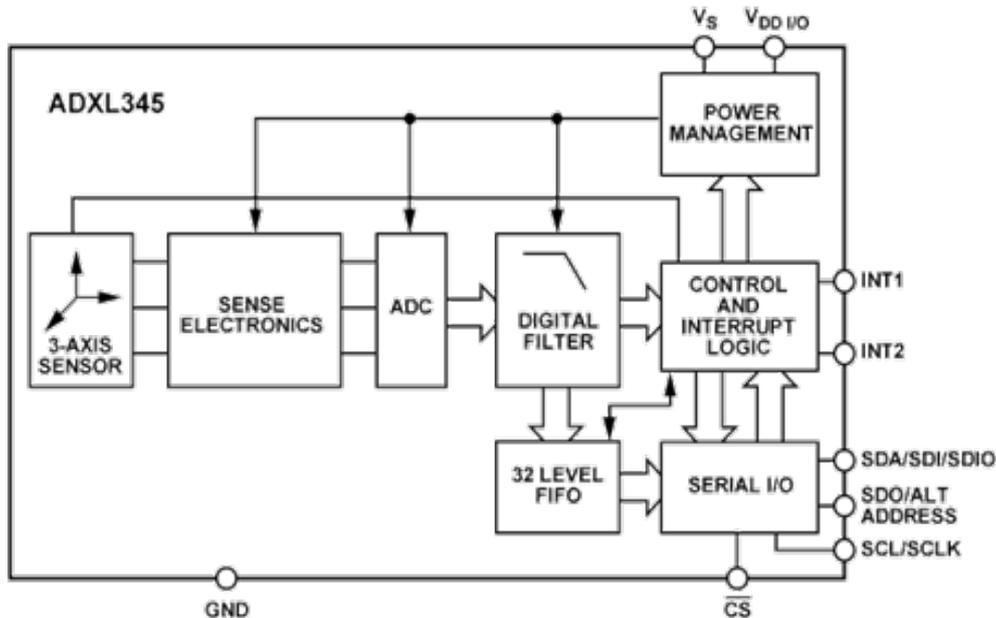
Fig.2. Block diagram of the ADXL 345 sensor chosen for the project

The ADXL335 sensor is a three-axis (X, Y and Z) analogue accelerometer capable of measuring accelerations in a typical range of ±3 g, making it suitable for vibration monitoring applications in structures and equipment. Its integration with an Arduino platform allows for the creation of a simple, flexible and low-cost data acquisition system [23], [26]. The analogue signals provided by the three outputs of the sensor are connected to the analogue inputs of the Arduino board, where they are converted into digital values using the internal analogue-to-digital converter (ADC).

For vibration monitoring, the acquired data is sampled at a frequency high enough to capture the relevant dynamic components and is then processed using digital filtering algorithms, such as the Butterworth filter, to reduce noise and eliminate unwanted components. The processed values can be transmitted to a computer or stored locally for spectral analysis and identification of dominant frequencies [5], [8], [12], [16].

The main advantage of this solution is its simplicity of implementation and the possibility of expansion with additional modules (wireless communication, SD card storage), which makes it suitable for continuous monitoring and preventive diagnostics of systems subject to vibrations [11], [15], [21].
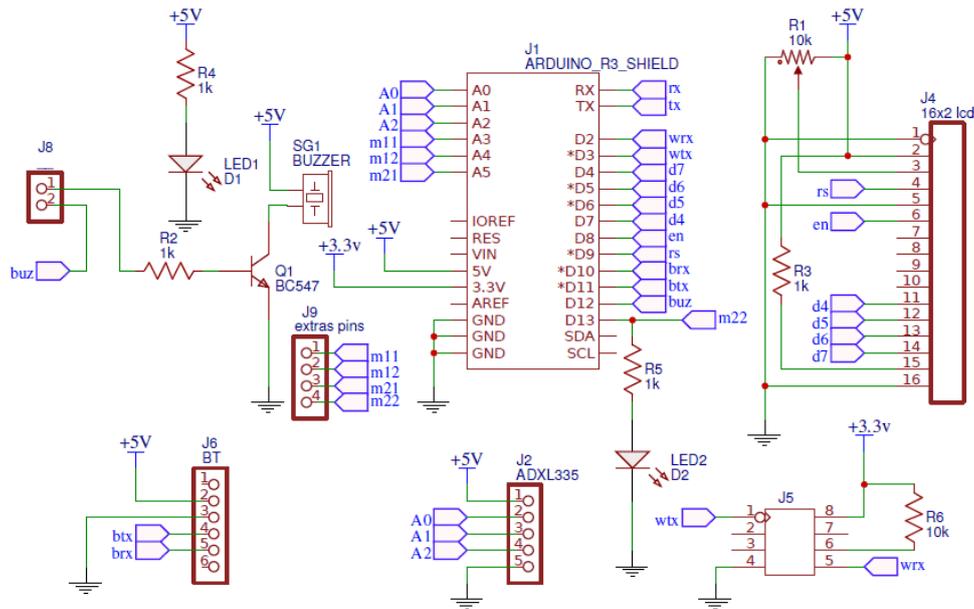
Fig.3. Electronic circuit of the earthquake detection system using the ADXL 345 MEMS sensor

3.1. Source code used in the microcontroller

After connecting the microcontroller to the computer, upload the following code:

```
//  - X-axis (Analogue Input 0)
//  - Y-axis (Analogue Input 1)
//  - Z-axis (Analogue Input 2)
//  - Vcc (+5V)
//  - GND (GND)

const int xPin = 0; // X-axis pin
const int yPin = 1; // Y-axis pin
const int zPin = 2; // Z-axis pin

void setup() {
        Initialise the serial port with a baud rate of 9600.
  Serial.begin(9600);
}

void loop() {
        Read the analogue inputs from the MEMS sensor.
  int xValue = analogRead(xPin);
  int yValue = analogueRead(yPin);
  int zValue = analogRead(zPin);
```

Convert the analogue input values to G-forces.

```
float xg = (xValue * 5.0 / 1023.0 - 1.5) / 0.3;
float yg = (yValue * 5.0 / 1023.0 - 1.5) / 0.3;
float zg = (zValue * 5.0 / 1023.0 - 1.5) / 0.3;
```

The forces are displayed on the screen via the serial port.

```
Serial.print("X-axis: ");
Serial.print(xg);
Serial.print(" g, Y-axis: ");
Serial.print(yg);
Serial.print(" g, Z-axis: ");
Serial.print(zg);
Serial.println(" g");
```

A delay of 100 milliseconds before reading the sensor again.

```
 delay(100);
}
```

This code reads the analogue input values from the X, Y, and Z pins of the ADXL335 sensor, converts them to g-force values, and then prints them to the Arduino IDE serial monitor. The analogueRead() function reads the analogue input values, and the conversion formula is taken from the ADXL335 sensor datasheet.

The Serial.print() function is used to print the g-force values to the serial monitor, and the delay() function is used to pause the program for 100 milliseconds before reading the sensor again [24], [25].

3.2. Real-time graph obtained from sensor data

To create the graph of the forces involved, the following code is used:

```
ADXL335 Accelerometer Sensor  – Real-time graph example
//   - X-axis (Analogue Input 0)
//   - Y-axis (Analogue Input 1)
//   - Z-axis (Analogue Input 2)
//   - Vcc (+5V)
//   - GND (GND)

const int xPin = 0; // X-axis pin
const int yPin = 1; // Y-axis pin
const int zPin = 2; // Z-axis pin

void setup() {
 // Initialise serial communication
 Serial.begin(9600);
}
```

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```
void loop() {
 // Read the analogue input values from the ADXL335 sensor
 int xValue = analogRead(xPin);
 int yValue = analogueRead(yPin);
 int zValue = analogueRead(zPin);

 // Convert the analogue input values to g-force (using the formula from the datasheet)
 float xg = (xValue * 5.0 / 1023.0 - 1.5) / 0.3;
 float yg = (yValue * 5.0 / 1023.0 - 1.5) / 0.3;
 float zg = (zValue * 5.0 / 1023.0 - 1.5) / 0.3;

        The G-force values are printed on the Serial Monitor port.
 Serial.print(xg);
 Serial.print(",");
 Serial.print(yg);
 Serial.print(",");
 Serial.println(zg);

        Plotting the G-forces graph on the Serial Plotter.
 Serial.flush(); // Wait for the Serial Plotter to catch up
}
```

This code is similar to the previous one, but instead of printing the g-force values on the serial monitor, it sends them to the serial plotter. The Serial.print() function is used to send the g-force values to the serial plotter in the format "x,y,z", where x, y, and z are the g-force values for the X, Y, and Z axes, respectively.

The Serial.flush() function is used to wait for the Serial Plotter to catch up before sending the next set of values. To plot the graph in the Serial Plotter, select "Serial Plotter" from the "Tools" menu in the Arduino IDE or press "Ctrl+Shift+L" on your keyboard.

3.3. Transmitting and storing data in Matlab

To obtain serial data from Arduino to Matlab, follow these steps:
- ➢ Connect the Arduino board to your computer using a USB cable.
- ➢ Open the Arduino IDE platform and upload the code to the board you want to use to send data to Matlab. Open Matlab and create a new script or function file.
- ➢ Use the "serial" command to create a serial object in Matlab that will communicate with the Arduino board. For example:

```
s = serial('COM3', 'BaudRate', 9600);
```

This creates a serial object called "s" that will communicate with the Arduino board on COM3 at a baud rate of 9600.

The serial port is opened by calling the "fopen" function with the serial object as the input argument:

fopen(e);

The data is read from the serial port using the "fscanf" function. For example:

data = fscanf(s, '%f');

This reads a floating point number from the serial port and stores it in the variable "data".
Close the serial port when you are finished by calling the "fclose" function:

fclose(e);

You can also use the "fread" function to read raw binary data from the serial port if your Arduino code sends binary data.
The baud rate specified in Matlab must match the baud rate specified in the Arduino code, otherwise the data will not be received correctly [12], [18].

3.4. Data sent in real time in Matlab

To represent real-time data from an accelerometer sensor connected to an Arduino board in Matlab, follow these steps:
Connect the Arduino to your computer using a USB cable and upload the code that reads the data from the accelerometer sensor and sends it via serial communication.
Open Matlab and create a new script or function file. Use the "serial" command to create a serial object in Matlab that will communicate with the Arduino board. For example:

s = serial('COM3', 'BaudRate', 9600);

This creates a serial object called "s" that will communicate with the Arduino board on COM3 at a baud rate of 9600.

Open the serial port by calling the "fopen" function with the serial object as the input argument:

fopen(s);

Create an empty array to store the data:

data = [];

Create a while loop that reads data from the serial port and stores it in the "data" array until the desired number of data points is reached:

```
while numel(data) < num_points
line = fscanf(s, '%f,%f,%f');
line_data = strsplit(line, ',');
data(end+1,:) = [str2double(line_data{1}) str2double(line_data{2})
str2double(line_data{3})];
end
```

Digital processing is used to filter signals in the detection of vibrations in wind turbines, and two of these filters are Butterworth and Kalman.

The Butterworth filter filters a signal to remove unwanted components (usually noise) and preserve the useful signal as faithfully as possible. Its distinctive feature is that it provides a very smooth response in the band, without ripples, making it one of the most widely used filters in engineering.

The main purpose of the Butterworth filter is to obtain the cleanest possible signal without distorting important frequencies.

Key features

1. No ripple in the passband

The Butterworth filter is also called a "maximally flat filter" because its passband is perfectly smooth—there are no oscillations like in Chebyshev or Elliptic filters. The useful signal is preserved as faithfully as possible.

2. Effectively eliminates noise outside the useful band

It has a progressive attenuation slope that increases with the order of the filter. It can eliminate electrical noise, unwanted vibrations, interference, etc.

3. It is ideal when the shape of the signal is important. Butterworth has relatively little effect on the shape of the signal over time.

Implementation in Matlab for filtering the signal from Arduino:

```
fs = 100;      % sampling frequency (Hz)
fc = 5;        % cutoff frequency (Hz)
order = 4;     % filter order

[b, a] = butter(order, fc/(fs/2), 'low');

data_filt_butter = zeros(size(data));

for k = 1:3
   data_filt_butter(:, k) = filtfilt(b, a, data(:, k));
end

figure;
plot(data_filt_butter);
title("ADXL345 - Butterworth Filter");
xlabel("Samples");
```

ylabel("Acceleration (raw)");
legend("X", "Y", "Z");
grid on;

Tower sway analysis is performed using structural dynamics models, modal analysis techniques, as well as monitoring systems based on accelerometers, gyroscopes and advanced filtering and estimation algorithms (e.g. Kalman, Butterworth filters, FFT spectral analysis).

Tower sway refers to the slow, low-amplitude oscillations of a tall structure caused by:
- wind
- earthquakes
- dynamic loads
- structural resonance
    The typical frequencies for such vibrations are low:
- **0.1 – 5 Hz** (depending on height and stiffness)

The accelerometer measures the total acceleration:

$$a(t) = a_{structure}(t) + a_{noise}(t) \tag{1}$$

where noise can come from:
- local vibrations
- electromagnetic interference
- electronic noise from the sensor

    For *tower sway* detection, we are only interested in low-frequency components. The following are used: Butterworth low-pass filter or band-pass filter centred on the natural frequency of the structure.

Using a filter has advantages
- Maximum flat response in the passband
- No ripple (does not distort the actual vibration amplitude)
- Good numerical stability
- Simple real-time implementation

The amplitude response of an nth-order analogue Butterworth filter is defined by the relationship:

$$\left| H(j\omega) \right| = \frac{1}{\sqrt{1 + \left(\dfrac{\omega}{\omega_c} \right)^{2n}}} \tag{2}$$

where:
- ω is the signal frequency,
- ω_c is the cutoff frequency,
- n is the order of the filter.

At the cutoff frequency, the amplitude decreases to from its maximum value, corresponding to an attenuation of -3 dB $\frac{1}{\sqrt{2}}$. The order of the filter determines the attenuation slope in the stop band: the higher the order, the steeper the transition between the pass band and the stop band (the slope is approximately 20n dB/decade).

The poles of the Butterworth filter are evenly distributed on a semicircle in the complex plane, which ensures stability and a smooth response characteristic.

To create a system for monitoring the oscillations of an experimental wind tower, an ADXL 345 sensor was used together with an ATMEL 328 microcontroller.
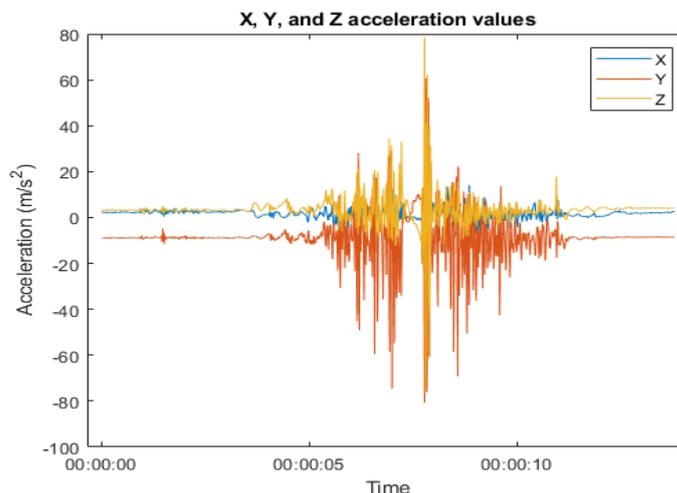
Fig.4. Saving data in Matlab via the serial port

This reads the data from the serial port and stores it in the "data" array until the "num_points" data points have been collected. The "fscanf" function reads a line of data from the serial port, which is then split into three numbers using the "strsplit" function. The three numbers are then converted to doubles and stored in the "data" array.

Ploting the data using the "plot3" function:
plot3(data(:,1), data(:,2), data(:,3), '.', 'Color', [1 0 0]);

This plots the data in a 3D diagram using the x, y, and z coordinates from the "data" array. The "." argument specifies that each data point should be represented as a point, and the "Colour" argument specifies that the colour should be red ([1 0 0]). You can use different colours for each axis by changing the colour argument.

4. CONCLUSIONS

The analysis of non-compliant vibrations of the wind turbine tower, performed on the basis of signals acquired using a MEMS accelerometer, demonstrated that this category of sensors is a viable and economical solution for continuous monitoring of the dynamic behaviour of the structure, providing adequate accuracy for structural diagnostic applications. The implementation of the Butterworth filter in the signal processing chain allowed for the effective attenuation of high-frequency noise and the isolation of relevant components of structural vibrations, maintaining an almost flat amplitude response in the passband, favourable for modal analysis.

The spectral results obtained after filtering highlighted frequency components located in the vicinity of the tower's natural frequencies, indicating the possibility of non-compliant vibration states associated with resonance and aeroelastic coupling phenomena. Correlating the acceleration values with the turbine operating regime and wind intensity showed that dynamic stresses increase significantly during transition intervals, such as start-up, shutdown and sudden speed variations, these regimes representing critical moments for structural integrity.

The study confirms that the use of a monitoring system based on MEMS sensors, combined with Butterworth digital filtering, can form the basis of a Structural Health Monitoring system capable of early detection of deviations from normal structural behaviour. The proposed methodology facilitates the identification of structural degradation trends and supports the adoption of predictive maintenance strategies, thus contributing to increasing the tower's lifespan and reducing operating costs.

At the same time, certain limitations of the proposed solution are highlighted, related to the sensitivity of MEMS accelerometers to temperature variations, the need for periodic calibration and the low resolution at very low frequencies, characteristic of the tower's high-amplitude oscillations. In the future, the integration of multiple sensors, the use of advanced signal processing techniques (wavelet analysis, adaptive filters) and the application of artificial intelligence-based methods may lead to a significant improvement in the accuracy of non-compliant vibration detection and an expansion of the monitoring system's capabilities.

In conclusion, tower oscillations are a fundamental aspect of the dynamic behaviour of modern wind turbines, with direct implications for structural safety, energy performance and operational life.

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OPTIMIZING PC–TRANSCEIVER INTERFACING FOR DIGITAL MODE OPERATION: GALVANIC ISOLATION AND RF INTERFERENCE CONTROL SOLUTIONS FOR THE FT-857D

ANDREI CRISTIAN RADA[1]

Abstract: The paper presents technical solutions for optimizing the interface between the PC and the Yaesu FT-857D transceiver for reliable operation of digital modes. Specific issues related to ground loops, unwanted couplings, and RF interference, which can affect signal quality and communication stability, are analyzed. The use of galvanic isolation via audio transformers and optocouplers on control lines is proposed, as well as filtering and shielding techniques to reduce radio frequency interference. The results show significant improvements in the signal-to-noise ratio and increased transmission reliability in digital modes such as PSK31, FT8, or RTTY.

Key words: Galvanic interfacing, Electromagnetic compatibility (EMC), Transformer audio isolation, RF digital modulations, ALC level control.

1. INTRODUCTION

The integration of modern digital equipment with high-power RF transceivers raises a number of challenges related to electromagnetic compatibility and the protection of sensitive circuits. The design features of some transceivers, such as the Yaesu FT-857D, require extra attention to the way the connections between the PC and the station are made, as the common ground between devices can promote unwanted coupling of radio frequency energy into the digital processing circuits. In the absence of adequate isolation solutions, these phenomena can lead to degraded reception performance, display instabilities, and, in extreme scenarios, damage to the computer's electronic components [2], [22], [24].

The experimental investigation presented revealed that direct interfacing, either via the CAT port or through Line-In/Line-Out audio connections, can introduce additional noise and disturbances during transmission.

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The implementation of galvanic isolation using audio transformers properly dimensioned for the 200 Hz – 4 kHz bandwidth proved to be an effective solution for suppressing these effects, ensuring stable operation at power levels of up to 100 W.

At the same time, optimizing audio signal levels and correctly adjusting the ALC are essential to avoid distortions in digital modulations, contributing both to transmission quality and to the protection of the transceiver's final amplifier stages.

This material aims to provide a systematic presentation of the observed phenomena, the implemented solutions, and the practical implications associated with safe PC-to-FT-857D transceiver interfacing in the context of digital mode operation.

2. CONSIDERATIONS REGARDING THE PC–FT-857D INTERFACE

In order to ensure stable communication between the computer and the FT-857D transceiver, the original CAT interface (CT-62) schematic was analyzed. Frequently published in the literature and technical communities (Fig. 1), this schematic relies exclusively on transistors for voltage level conversion; however, it presents considerable risks to the integrity of the equipment [2], [9], [14].
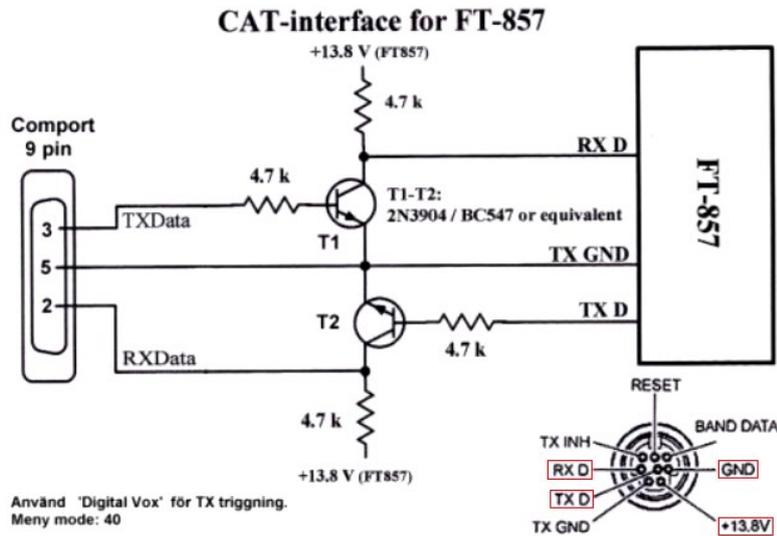
Fig.1. CAT interface diagram

Standard RS-232 levels can reach values of ±18 V, which may lead to damage to the transceiver's RXD/TXD lines if accidental voltages of approximately 36 V are applied. Since the transceiver's CAT logic operates at 0–5 V levels, the use of such a minimalist scheme cannot be considered suitable for safe and robust applications [23].

A significantly more reliable technical solution is represented by the schematic shown in Fig. 2, which employs the MAX232 integrated circuit for voltage level conversion.

This circuit provides bidirectional conversion between ±18 V (RS-232 standard) and the 0–5 V logic levels required by the CAT interface. Voltage regulation

is achieved using a 78L05 regulator, powered directly from the transceiver's 13.8 V supply. The MAX232 internally generates the voltages required for RS-232 signaling, producing approximately +15 V and −15 V at its outputs (pin 13) through a voltage multiplication/tripling mechanism.
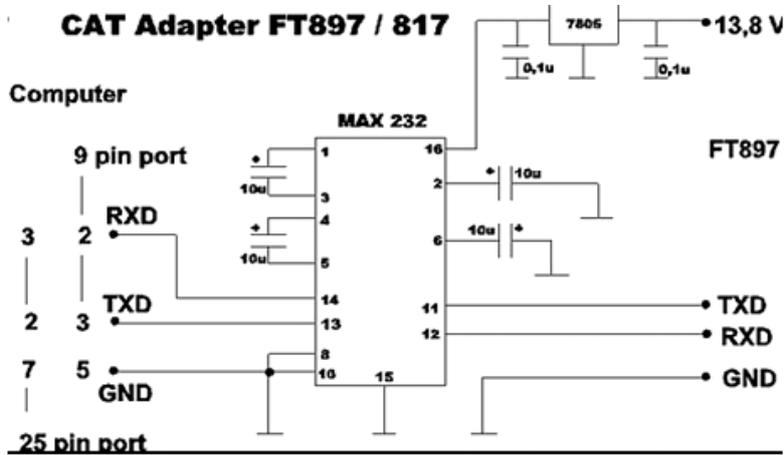
Fig.2. Schematic of a CAT interface with MAX232 specialized IC

The conversion in the opposite direction, from the PC to the transceiver, is achieved by limiting the input voltages to compatible levels (0–5 V) at pin 11 (TXD), regardless of variations of the input signal within the ±18 V range.

The implementation of such a dedicated interface eliminates the vulnerabilities of simple transistor-based circuits and provides the necessary protection for the safe operation of the transceiver in digital applications [1], [4], [16].

An additional aspect that requires attention is the fact that the FT-857D transceiver's CAT interface shares the same ground (GND) as the personal computer. As long as the transceiver operates exclusively in receive mode, this configuration does not pose major problems. However, when switching to transmit mode at a power level of 100 W, parasitic radio-frequency (RF) coupling may occur toward the computer's circuitry, including the motherboard, with the potential to damage sensitive components. For this reason, the use of an interface without galvanic isolation cannot be considered a safe solution, even if the actual risk may initially appear difficult to assess [25].

3. OPTIMIZATION OF THE PC–TRANSCEIVER INTERFACE

The practical implementation of the manufacturer-provided schematic demonstrated certain limitations. Although the Ham Radio Deluxe (HRD) software established the CAT connection without difficulty, a slight increase in receiver noise was observed immediately after installation. The connection operated correctly at all baud rates, including the maximum value of 38,400 bps; however, this behavior did not eliminate concerns regarding susceptibility to RF interference. Subsequently, when the transceiver was switched to transmit mode, visible disturbances appeared on the

monitor display (manifested as line fluctuations), indicating the coupling of RF signals into the computer's video circuitry [5], [15].

Following these observations, the section concerning the audio connection between the PC sound card and the FT-857D transceiver was also reconsidered. The direct connection, implemented according to the schematic shown in Fig. 3, proved to be inadequate [26].
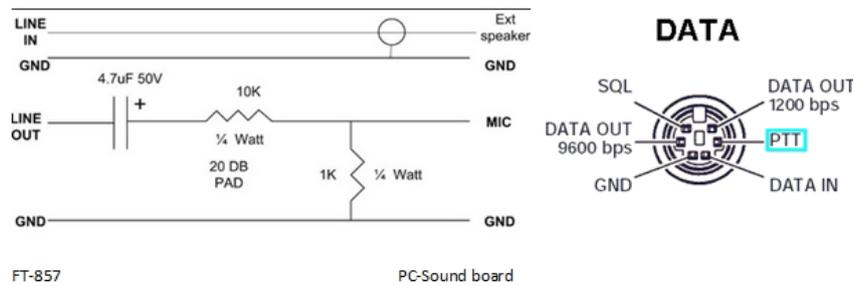
Fig. 3. Connection between the Sound Card and the FT-857D

The configuration used was as follows:
- Line Out (PC) → DATA OUT 1200 bps (transceiver);
- Line In (PC) → DATA IN (transceiver);
- GND (PC) → GND (transceiver).

Through this connection, the transceiver ground and the computer ground were directly linked, which increases the risks of RF coupling and the occurrence of unwanted currents between the devices [21]. Consequently, this configuration should be considered unsuitable for stable operation in digital modes.

From an operational standpoint, reception results were initially satisfactory, allowing the first digital-mode communication to be established (Fig. 4). The Digital Master 780 software interface included in the HRD package indicated correct operation under these conditions. However, the performance achieved does not justify the risks associated with such a direct connection, and therefore the use of a scheme without galvanic isolation cannot be rigorously recommended [6], [10], [17].
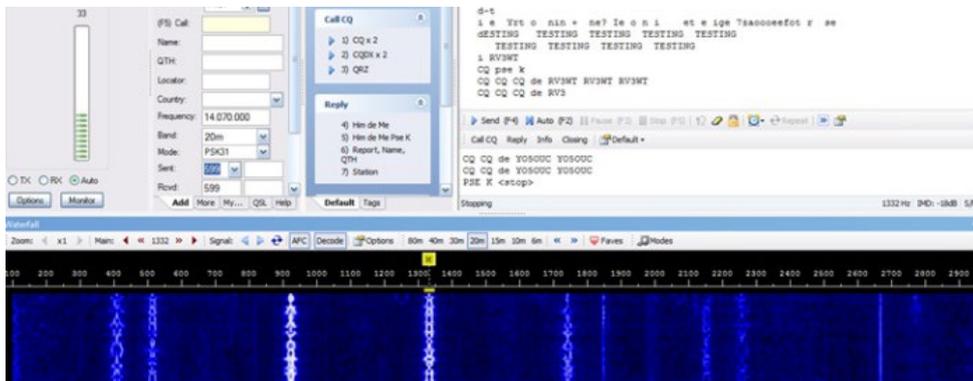
Fig. 4. Reception results enabling digital-mode communication

The audio signal levels could be properly adjusted, both on reception via the sound card's Line In control and on transmission via the transceiver's volume adjustment. Under these conditions, PSK31 signals began to be correctly received, and the initial segments of communications (QSOs) were decoded without difficulty. However, upon switching to transmit mode, in addition to the previously observed fluctuations on the monitor display, a much more serious issue occurred: the computer's network card temporarily disconnected. This behavior clearly indicated the presence of unwanted RF coupling into the PC's internal circuits, representing an obvious risk to system integrity [11], [13], [18].

Under these circumstances, it became necessary to explore a solution that would provide galvanic isolation between the transceiver and the computer, enabling the safe use of digital modes. A CAT interface schematic incorporating isolation elements was identified (Fig. 5). In this version, the MAX232 circuit was powered from the RTS and DTR lines of the serial port, eliminating dependence on the transceiver's power supply and reducing exposure to parasitic RF signals. Additionally, the use of 4N27 optocouplers, characterized by low switching times, ensured compatibility with high transfer rates of up to 38,400 bps.
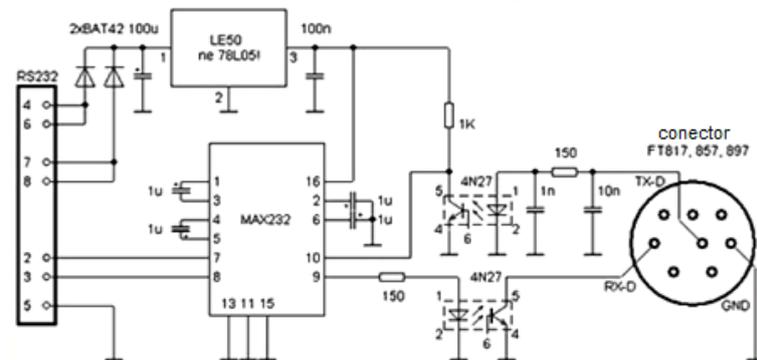
Fig. 5. CAT interface schematic with galvanic isolation subjected to modifications

Although the assembly was carefully constructed, the interface did not function correctly: the transceiver failed to establish the CAT connection. Oscilloscope investigation revealed the cause. The transceiver's RXD and TXD lines are normally in a logic "1" state, corresponding to a +5 V voltage. When a +18 V signal from the PC appears on pin 8 of the MAX232, pin 9 outputs +5 V, lighting the optocoupler LED through a 150 Ω resistor. This saturates the optocoupler transistor, causing the voltage at the collector to drop to approximately 0.2 V — equivalent to a logic "0" at the transceiver's RXD input. Consequently, the signal logic is inverted, making CAT communication impossible. The same phenomenon occurs in the opposite direction.

Once the cause was identified, the possibility of correcting the behavior in software was analyzed; however, neither the FT-857D transceiver nor the HRD program allows inversion of the CAT signal logic. The only viable solution was to modify the electrical schematic.

Thus, the schematic in Fig. 5 was adapted to correctly reproduce the required voltage levels: when the serial port provides +18 V, the interface RXD input must receive +5 V, and when −18 V is transmitted, the level must drop to 0 V. To achieve this, pin 2 of the 4N27 optocoupler was connected to pin 9 of the MAX232, and pin 1 of the optocoupler was tied to the +5 V line through a 1 kΩ resistor. To prevent overloading the MAX232 pin 9 output, a transistor buffer using a BC107 transistor was introduced to supply the current needed to drive the optocoupler LED.

The modified schematic was designed using Eagle version 6.4.0 and is shown in Fig. 6.
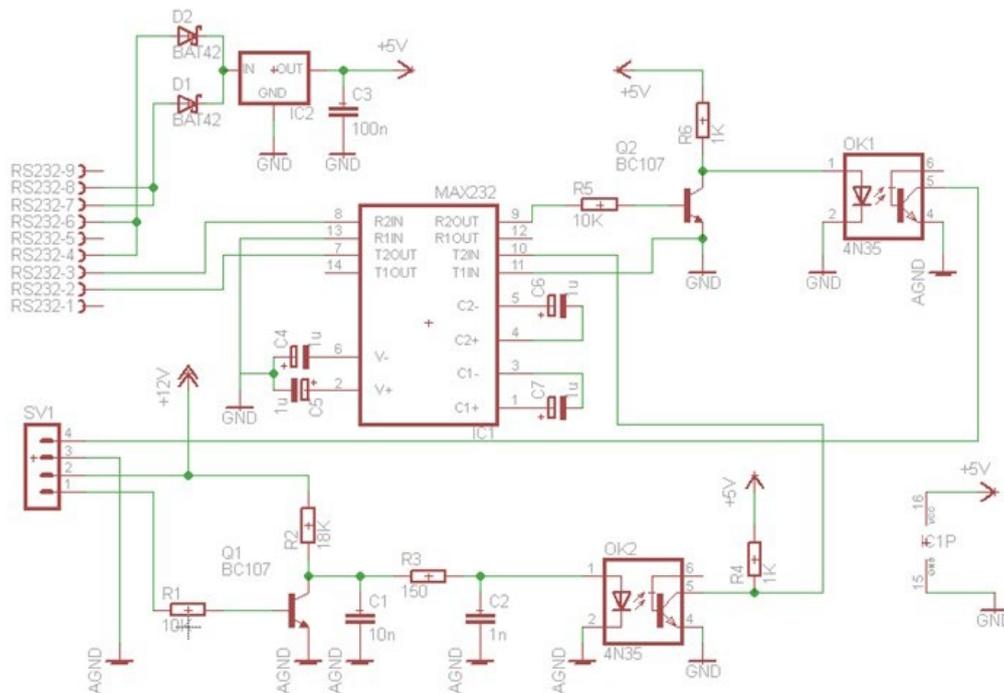
Fig. 6. Electrical schematic of the CAT interface, suitable for the FT-857D

The SV1 connector of the interface connects to the FT-857D transceiver's CAT port as follows:

- Pin 1 (SV1) → TXD (CAT – rear of transceiver);
- Pin 2 (SV1) → +13.8 V (CAT – rear of transceiver);
- Pin 3 (SV1) → AGND (transceiver ground);
- Pin 4 (SV1) → RXD (CAT – rear of transceiver).

The IC2 (78L05) circuit provides voltage stabilization at +5 V. The transceiver ground, labeled AGND, is completely isolated from the PC ground, labeled GND, ensuring the required galvanic separation. The MAX232 is powered from the PC via the serial port, using pins 4, 6, 7, and 8 of the DB9 connector, with RTS and/or DTR selected in the HRD settings for operation. The LED on the return path, belonging to

optocoupler OK2, is powered from the transceiver and is optically isolated from the MAX232 and, consequently, from the computer [7], [19].

Tests performed on the modified interface confirmed stable operation at all available transfer rates, while the electromagnetic noise associated with directly connecting the PC and transceiver grounds was completely eliminated. Galvanic isolation thus demonstrated solid effectiveness, ensuring safe interfacing between the PC and the FT-857D, regardless of the transmission power level used.

Regarding the audio connection, the configuration shown in Fig. 3 proved unacceptable because it does not provide the necessary isolation between the computer ground and the transceiver's RF ground. To eliminate this issue, a solution based on galvanic isolation using audio transformers was adopted. A standard 220/12 V transformer (ratio 20:1) was used, connected in reverse compared to typical usage: the low-voltage winding (12 V), with low impedance, was connected to the sound card output, while the 220 V winding, with much higher impedance, was connected to the transceiver. To ensure isolation in both directions, two small transformers (400 mA) were used, as indicated in the area marked in Fig. 7.

Fig. 7. Use of transformers on the audio line between the PC and the FT-857

This solution, although technically simple, proved effective because the 220/12 V transformers have a sufficiently wide usable bandwidth (approximately 200 Hz – 4 kHz), suitable for digital mode transmission. The low impedance of the winding connected to the PC contributes to significant attenuation of unwanted RF signals — by approximately 13 dB, according to the transformation ratio — thereby reducing parasitic coupling from the transceiver during transmission. Practical tests confirmed that galvanic isolation completely eliminates RF disturbances affecting the monitor and PC peripherals, without impairing reception or transmission performance [20].

Although there are solutions superior in terms of linearity — such as those based on optocouplers specialized for the audio domain, as described in the literature — the transformers used here proved adequate for operation at 100 W. For higher power levels, adopting the solution from the cited references could be justified.

4. ADJUSTMENT OF AUDIO LEVELS AND ALC

Proper adjustment of the sound card level and the ALC (Automatic Level Control) parameter is essential for distortion-free transmission in digital modes. The recommended procedure involves switching the transceiver to transmit mode and adjusting the audio output level until the ALC meter displays two to three bars on the dedicated FT-857D display. Subsequently, the peak power is checked in PWR mode, which should reach the upper limit of the scale for a nominal power of 100 W. Slightly reducing the audio level immediately lowers the peak power, while excessively increasing the audio level does not further increase peak power, but only the average power, indicating RF amplifier saturation and the onset of distortion (see Fig. 8) [3].
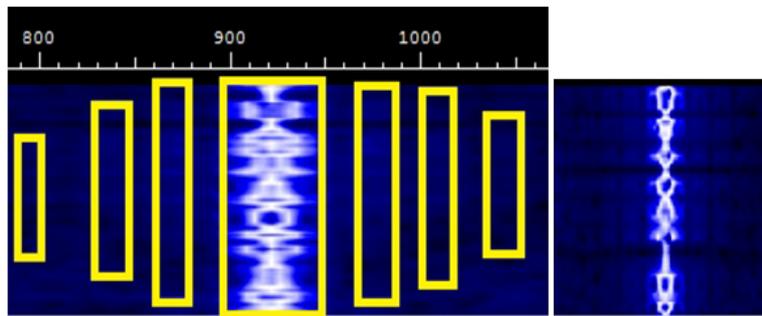

Fig. 8. Representation of a distorted PSK31 signal

It is recommended to use a minimal Digital Gain (the default value is 50; in the presented tests, a value of 5 was used) to minimize the risk of distortion.

Adjusting the audio output level is crucial, as an excessively high level leads to saturation of the RF final stage. This phenomenon introduces significant nonlinearities, severely affecting digital modulations—distortions that cannot be compensated by increasing the transmission power [8], [12].

For optimal adjustment, the audio processor (PROC) of the FT-857D transceiver should be disabled in digital modes, as it introduces compression and distortions incompatible with PSK modulations. Operating without the audio processor is therefore an essential condition for maintaining the integrity of the transmitted signal.

5. CONCLUSIONS

Direct connections between the PC and FT-857D, whether through the CAT port or audio lines, introduce significant risks, including RF coupling, ground loops, and unwanted currents, which can compromise both signal quality and the safety of equipment.

Implementing galvanic isolation, both for CAT signals (using optocouplers and MAX232 circuitry) and audio signals (using audio transformers), proved highly effective in eliminating RF interference, ensuring safe operation, and maintaining signal integrity at transmission powers up to 100 W.

The modified CAT interface with optocouplers and proper voltage-level adjustments ensures correct logic signal transmission, stable connection at all supported baud rates (up to 38,400 bps), and protection of both the PC and transceiver from damage.

Using 220/12 V transformers in reverse connection for the audio lines provides adequate bandwidth (200 Hz – 4 kHz) for digital modes and attenuates parasitic RF signals by approximately 13 dB, effectively preventing interference with PC peripherals and display devices.

Correctly setting the audio output level and ALC is essential to avoid RF amplifier saturation and signal distortion. Overdriving the audio signal leads to nonlinearities that degrade digital modulations such as PSK31 and cannot be corrected by increasing transmission power.

The FT-857D audio processor (PROC) must be disabled in digital modes to prevent compression and distortion, ensuring accurate and clean signal transmission.

The combination of galvanic isolation, careful audio and CAT interfacing, and proper signal level adjustments allows stable, high-quality operation of digital modes, safeguarding both the transceiver and the computer while maximizing transmission and reception performance.

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RISK ASSESSMENTS IN TERMS OF OCCUPATIONAL HEALTH AND SAFETY FOR 400/220/110/20 kV IERNUT POWER SUBSTATION

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Abstract: This paper presents a comprehensive Occupational Health and Safety (OHS) risk assessment for the 400/220/110/20 kV Iernut power substation, a critical node in the regional transmission network. Owing to the complexity of high-voltage installations and the diverse operational activities involved, workers are exposed to a broad range of hazards, including electrical, mechanical, thermal, ergonomic, and environmental risks. The study applies established OHS methodologies – such as hazard identification, risk matrix evaluation, and Failure Mode and Effects Analysis (FMEA) – to systematically classify and prioritize risks associated with equipment operation, maintenance procedures, switching activities, and emergency scenarios. Findings indicate that the most severe risks relate to arc-flash events, electric shock, equipment failure during high-voltage maneuvers, and exposure to electromagnetic fields. Additional moderate to high risks include working at heights, confined-space hazards, and chemical exposure from insulating and cooling agents. Based on the assessed risk levels, the paper proposes a set of targeted control measures: engineering protections, procedural improvements, advanced personal protective equipment (PPE), enhanced training protocols, and real-time monitoring systems. The study underscores the importance of continuous risk reassessment and safety culture development to ensure reliable operation and worker protection within high-voltage substations.

1. DESCRIPTION OF THE NRDIOS BUCHAREST METHOD FOR RISK ASSESSMENT IN TERMS OF OCCUPATIONAL HEALTH AND SAFETY (OHS)

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The method developed by National Research and Development Institute of Occupational Safety "Alexandru Darabont" – NRDIOS Bucharest, aims to determine the quantitative level of risk/safety for a workplace, sector, section or company, based on a systemic analysis and assessment of risks of injury and occupational disease, in terms of OHS. The application of the method is finalised with a summary document – *Assessment Sheet of Workplace*, which includes the *global risk level of the workplace.*

The developed assessment sheet of the workplace is the basis of the program for the prevention of accidents and occupational diseases for the workplace, sector, section or company analysis. The essence of the method is to identify all risk factors in the system analysis (workplace) on the basis of pre-established control lists and to quantify the risk dimension on the basis of the combination of the severity and frequency of the maximum foreseeable consequence [1], [14], [19].

The global risk level (Nr) per workplace shall be calculated as a weighted average of the risk levels established for the identified risk factors. In order for the result obtained to reflect as accurately as possible the reality, the risk factor ranking, which is equal to the level of risk, shall be used as a weighting element [6], [20]. In this way, the highest risk factor will also be the highest ranking. Thus, it is eliminated the possibility for the cross-compensation effect, involved by any statistical average, to mask the presence of the highest-risk factor [2], [10], [13].

The formula for calculating the *global risk level* is the following:

$$N_r = \frac{\sum_{i=1}^{n} r_i \cdot R_i}{\sum_{i=1}^{n} r_i} \tag{1}$$

where:
N_r - *the level of global risk in the workplace;*
r_i - *risk factor ranking „i";*
R_i - *level of risk for the risk factor „i";*
n - *number of risk factors identified at the workplace.*

The level of security (Ng) at workplace is identified on the risk/security level mapping scale, built on the opposite proportionality of risk and security levels. Both the global risk level and the safety level are recorded in the workplace sheet. In the case of macro-systems assessment (sector, section, company), the weighted mean of the average safety levels determined for each workplace analysed in the macro-system component (similar workplace are considered as a single workplace) has to be calculated so that to obtain the *global level of safety at work* for the workshop/section/sector or enterprise under investigation – Ng: [11], [15], [18].

$$N_g = \frac{\sum_{p=1}^{n} r_p \cdot N_{rp}}{\sum_{p=1}^{n} r_p} \tag{2}$$

where:
- **Ng** = *the overall risk level of the power substation;*
- **rp** = *workplace rank p, equal to the risk level of the workplace;*
- **n** = *number of workplaces;*
- **Nrp** = *is the level of overall workplace risk.*

The authors of the NRDIOS method recommended that the maximul acceptable risk level be 3,5.

2. RISKS ASSESSMENT IN TERMS OF OHS (ACCIDENTS AND OCCUPATIONAL ILLNESS) AT A 400/220/110/20 kV IERNUT POWER SUBSTATION WITHIN NATIONAL POWER SYSTEM

The 400/220/110/20 kV Iernut power substation is located in Iernut commune, Mures county, belonging to the Sibiu Electricity Transport Unit, according to fig. 1., represents an important power node of the Romanian Power System, through which the electricity produced in the Iernut Thermal Power Plant is discharged and the transfer of electricity to the Transylvania and Moldova regions.

Fig.1. Positioning of the 400/220/110/20 kV Iernut power substation
(source:www.transelectrica.ro)

The overall risk levels determined for each workplace at the 400/220/110/20 kV power substation are generally as follows *(table 1.):*

Table 1. **Workplaces at the 400/220/110/20 kV power substation**

No.	WORKPLACE	LEVEL OF RISK (Nrp)
1	400, 220 kV, 110 kV OPERATING SERVICE	X
2	20 kV OPERATING SERVICE	X
3	400, 220 kV, 110 kV PRIMARY CIRCUIT MAINTENANCE	X
4	20 kV PRIMARY CIRCUIT MAINTENANCE	X
5	SECONDARY CIRCUIT MAINTENANCE	X

2.1. Risk level assessment for the activity: 400, 220 kV, 110 kV Operational Service

The object of the activity is the operational service of the power installations: *supervision; control; maneuver* [3], [5].

1. Means of production:

400 kV Power Substation:
The 400 kV power substation is of the external type and is equipped with two bussbar systems to which the following power cells (switchgears) are connected next OHL: 400 kV Gadalin and 400 kV South Sibiu.

220 kV Power Substation
The 220 kV power substation is of the external type and is equipped with two bussbar systems to which the following power cells (switchgears) are connected next OHL: 220 kV Ungheni, 220 kV Baia Mare 3 and 220 kV Campia Turzii.

110 kV Power Substation:
The 110 kV power substation is of the external type and is equipped with simple bussbar systems, to which the following power cells (switchgears) are connected all consumers to distribution network.

Risk factors specific to the means of production:
- *mechanical risk* (falling from the same level, slipping or tripping, explosions of equipment with a lifetime exceeded, falling from a height); *electrical risk* (direct contact with electrical installations); *thermal risk* (burns due to electric arc).

2. Work load:

According to the operating regulations, the duties of the operational staff are as follows: *performing the handover-receiving operations of the work team; supervision activity; control activity; the activity of executing the electric maneuvers.*
Risk factors specific to the work load:
- psychic stress in the 400 kV, 220 kV and 110 kV power substations, when installing shortcircuits by hand.

3. Performer:

The following staff works in the power substation: *manager (s) of the power substations (electrical engineer); shift leaders; shift leaders aides.*
Risk factors specific to the performer:
- *wrong action:* incorrect identification of the installation and non-verification of the lack of voltage, when mounting the short circuits; failure to respect the neighbouring distances with risk of electric shock by direct contact; not checking the lack of voltage before mounting the mobile short circuits [4], [16].
- *omissions:* omissions of operations during manoeuvres, with risk of burns caused by electric arc, when closing grounding knives or mounting the mobile short circuits without checking the lack of voltage; non-use and/or non-verification of the personal protective equipment provided and/or of the electrical insulating means and devices.

4. Work environment:
The operating staff carries out the activity in the control room at the external power substations of 400 kV, 220 kV and 110 kV, where the specific nature of the work assignment requires operation and control activities regardless of climatic conditions and as a result the main risk factor specific to the working environment is

the air temperature by exposure to high or low temperatures during the performances of the work assignment [7], [9], [17].

Risk factors specific to the work environment:

- *physical risk factors:* exposure to adverse weather conditions (low/high temperatures, rain, snow, air currents) during installations' control.

Table 2. **Workplace assessment sheet 400 kV, 220 kV and 110 kV Operational Service**

NATIONAL POWER SECTOR		ASSESSMENT SHEET OF WORKPLACE	NUMBER OF EXPOSED PERSONS			
RESPONSIBLE NATIONAL COMPANY			EXPOSURE TIME: hours/shift			
400 kV, 220 kV and 110 kV OPERATIONAL SERVICE			ASSESSMENT TEAM:			
The composition of the work system	Identified risk factors	Concrete form of manifestation of risk factors	Maximum foreseeable consequence	Class of severity	Class of probability	Risk level
Means of production means of production means of production means of production means of production	Mechanical risk factors: falling from level	1. Falling due to distraction when moving through outside power substations	Temporary Work Incapacity 3–45 days	2	1	1
	Electrical risk factors: electrical shock hazard	2. Not using two mobile short circuits in the working area	DEATH	7	2	2
	Electrical risk factors: electrical shock hazard	3. Not using in working area of capacitive load damper (in case of capacitive currents)	DEATH	7	2	2
	Thermal risk factors: explosion hazard	4. Explosion of power, voltage, and current transformers, discharge	DEATH	7	1	3
Performer	Wrong actions: omission of present operations; not using means of protection	5. Not checking the lack of voltage before mounting the mobile short circuits	DEATH	7	2	2
		6. Failure to use/verify personal protective	DEATH	7	1	3

		equipment, tools and electro-insulating devices provided				
Work environment work environment	Risk factors: air temperature	7. Exposure to adverse weather conditions (high, low temperatures) when operating in outdoor power substations	Temporary Work Incapacity	2	1	1

The global risk level at workplace: 400 kV, 220 kV and 110 kV Operational Service

$$N_{400kV-220kV} = \frac{\sum_{i=1}^{7} R_i \cdot r_i}{\sum_{i=1}^{7} r_i} = \frac{2 \cdot (1 \cdot 1) + 3 \cdot (2 \cdot 2) + 2 \cdot (3 \cdot 3)}{2 \cdot 1 + 3 \cdot 2 + 2 \cdot 3} = \frac{32}{14} = 2,28 \qquad (3)$$

2.2. Risk level assessment for activity: 20 kV Operational Service

The object of the activity is the operational service of the power installations: *supervision; control;maneuver* [8].

1. Means of production:
20 kV Power Substation:

The 20 kV power substation is of the internal type and is equipped with double bussbar systems conected with longitudinal couple, to which the all power cells (switchgears) are connected: 20 kV OHLs; 20 kV Longitudinal Couple; 20 kV Measure; TSI 1 20/0,4 kV – 400 kVA (internal services); TSI 2 20/0,4 kV – 400 kVA (internal services).

Risk factors specific to the means of production: *mechanical risk* (falling from the same level, slipping or tripping, explosions of equipment with exceeded lifetime, falling from a height); *electrical risk* (direct contact with electrical installations); *thermal risk* (burns due to electric arc).

2. Work load:
According to the operating regulations, the duties of the operational staff are as follows: *performing the handover-receiving operations of the work team; supervision activity; control activity; the activity of executing the electric maneuvers.*

Risk factors specific to the work load: psychic stress in the 20 kV power substations, when installing short circuits by hand.

3. Performer
The following staff works in the power substation: *manager (s) power substations (electrical engineer); shift leaders; shift leaders aides.*

Risk factors specific to the performer:

- *wrong action:* incorrect identification of the installation and non-verification of the lack of voltage, when mounting the short circuits; failure to respect the neighbouring distances with risk of electric shock by direct contact; not checking the lack of voltage before mounting the mobile short circuits.

- *omissions:* omissions of operations during maneuvers, with risk of burns caused by electric arc, when closing grounding knives or mounting the mobile short circuits without checking the lack of voltage; non-use and/or non-verification of the personal protective equipment provided and/or of the electrical insulating means and devices.

4. Work environment:

Risk factors specific to the work environment: *physical risk factors:* exposure to adverse weather conditions (low/high temperatures, rain, snow, air currents) during installations' control.

Table 3. **Workplace assessment sheet 20 kV Operational Service**

NATIONAL POWER SECTOR RESPONSIBLE NATIONAL COMPANY 20 kV OPERATIONAL SERVICE		ASSESSMENT SHEET OF WORKPLACE		NUMBER OF EXPOSED PERSONS		
				EXPOSURE TIME: hours/shift		
				ASSESSMENT TEAM:		
The composition of the work system	Identified risk factors	Concrete form of manifestation of risk factors	Maximum foreseeable consequence	Class of severity	Class of probability	Risk level
MEANS OF PRODUCTION	Mechanical risk factors: Hazard movements: movement under propulsion	1. Short circuit breaker explosions	DEATH	7	1	3
		2. Discharging explosions during operation	DEATH	7	1	3
	Electrical risk factors: electric current	3. Touching of unmarked terminals and installations	DEATH	7	1	3
		4. Touching live installations when connecting short circuits	DEATH	7	1	3
		5. Touching the 20 kV busbars during maneuvers	DEATH	7	1	3
	Thermal	6. Burns due to short circuits	DEATH	7	1	3

WORK LOAD	Inadequate work load content relative to requirements security	7. Mounting short circuits by hand	DEATH	7	1	3
PERFORMER	Wrong actions	8. Failure to respect the neighbouring distances with risk of electric shock by direct contact.	DEATH	7	1	3
		9. Failure to verify the position and/or condition of the components to be operated when maneuvering	DEATH	7	1	3
	Omissions: omission of operations present in the Maneuver Sheet	10. Not checking the lack of voltage before installing mobile short circuiting or closing the grounding knives	DEATH	7	1	3
	Omissions: not using means of protection	11. Failure to use or check personal protective equipment, tools and electro-insulating devices	DEATH	7	1	3

The global risk level at workplace: 20 kV Operational Service

$$N_{20\,kV} = \frac{\sum_{i=1}^{11} R_i \cdot r_i}{\sum_{i=1}^{11} r_i} = \frac{11 \cdot (3 \cdot 3)}{11 \cdot 3} = \frac{99}{33} = 3,00 \qquad (4)$$

2.3. Risk level assessment for activity: 400 kV, 220 kV and 110 kV Primary Circuit Maintenance

The purpose of maintenance and repair of primary equipment is the following types of work: *servicing primary equipment; mechanical activities; welding and painting activity; masonry repair; dismantling of appliances.*

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1. Means of production:

Risk factors specific to the means of production:
- *mechanical risk factors:* hazardous movements; cutting edges and sharp corners when replacing broken insulators; explosion of molten metal particles or electric shock to electric welding; explosions at transformers.

2. Work load:

Work load of the service and repair team is to: *technical revisions (TR) – annually on all equipment in the power substations; current revisions (RC) – changes in sub-assemblies, replacement of power substation components; accidental interventions – in the event of faults or failures in primary equipment; maintenance of auxiliary installations; maintenance work on the power substation; changes of lighting fittings.*

Risk factors specific to the work load: failure to properly prepare and/or failure to comply with the required steps in the performance of maintenance activities; failure to comply with measures to ensure the working area; oversized physical effort when removing the cutting-off switches from the switchgears.

3. Performer:
The service-repair team the primary equipment is composed of electricians who are led by a master.
Risk factors specific to the performer:
- *wrong action:* misidentification of the installations in which work is being carried out; wrong maneuvers when performing operational tests; exceeding proximity distances when transporting materials to the work area and during work; displacement, stationing in hazardous areas outside the working area; falling from the same level by unbalancing, during the transport of materials within the area of the power substation,
- *omissions:* non-use of personal protective equipment as provided or use of non-certified personal protective equipment.

4. Work environment: *Risk factors specific to the work environment*

Table 4. **Workrkplace assessment sheet 400 kV, 220 kV and 110 kV Primary Circuit Maintenance**

NATIONAL POWER SECTOR		ASSESSMENT SHEET OF WORKPLACE		NUMBER OF EXPOSED PERSONS		
RESPONSIBLE NATIONAL COMPANY						
400 kV, 220 and 110 kV PRIMARY CIRCUIT MAINTENANCE				EXPOSURE TIME: hours/shift		
				ASSESSMENT TEAM:		
The composition of the work system	Identified risk factors	Concrete form of manifestation of risk factors	Maximum foreseeable consequence	Class of severity	Class of probability	Risk level

MEANS OF PRODUCTION	Mechanical risk factors: functional movements of technical machinery	1. Displacement by means of transport to the workplace – road accident;	DEATH	7	1	3
	Mechanical risk factors: functional movements of technical machinery	2. Hazardous surfaces	Temporary Work Incapacity	2	2	2
	Thermal risk factors	3. Injury by the thermal effect of the electric arc for service and repair personnel when traveling on the area of power substations for fulfilling the work load	1st degree Disability	6	1	3
	Electrical risk factors: indirect touch	4. Touching of metal parts accidentally under voltage, in conditions of: - damage to insulation from the metal housing; - failure of the protective connection	DEATH	7	2	3
WORK LOAD	Improper content in relation to security requirements	5. Improper preparation and/or non-compliance with mandatory steps and measures to secure the work area	DEATH	7	1	3
	Under/oversized workload in relation to the capacity of the performer	6. Dynamic, static effort, forced working positions at ground and height when handling and replacing subassemblies and components of primary equipment, insulators replacement	Temporary Work Incapacity 45-180 days	3	2	2

WORK ENVIRONMENT	Physical risk factors	7. Inhalation of toxic dust and gases in the while performing painting operations	Temporary Work Incapacity 45-180 days	3	2	2
PERFORMER	Wrong actions	8. Incorrect identification of the installations in which they work, wrong maneuvers when performing functional tests	DEATH	7	1	3
		9. Entering the work area unprepared in terms of work safety	DEATH	7	1	3
		10. Incomplete work permit without specifying all working area insurance conditions	DEATH	7	2	3
		11. Exceeding neighbouring distances of materials to the work area and during the works	DEATH	7	1	3
		12. Displacement, stationing in hazardous areas outside the working area	DEATH	7	1	3
		13. Falling from the same level through imbalance during the transport of materials to the power substation	Temporary Work Incapacity 3-45 days	2	1	1
	Omissions	14. Not using the personal protective equipment provided or use	DEATH	7	1	3

		of non-certified personal protective equipment				

The global risk level at workplace: 400 kV, 220 kV and 110 kV Primary Circuit Maintenance

$$N_{400-220kV} = \frac{\sum_{i=1}^{14} R_I \cdot r_i}{\sum_{i=1}^{14} r_i} =$$
$$= \frac{1 \cdot (1 \cdot 1) + 3 \cdot (2 \cdot 2) + 10 \cdot (3 \cdot 3)}{1 \cdot 1 + 3 \cdot 2 + 10 \cdot 3} = \frac{103}{37} = \mathbf{2,78} \tag{5}$$

2.4. Risk level assessment for activity: 20 kV Primary Circuit Maintenance

The purpose of maintenance and repair of primary equipment is the following types of work: *servicing primary equipment; mechanical activities; welding and painting activity; masonry repair; dismantling of appliances.*

1. Means of production: 20 kV Power Substation:

Risk factors specific to the means of production:
- *mechanical risk factors:* hazardous movements; cutting edges and sharp corners when replacing broken insulators; explosion of molten metal particles or electric shock to electric welding; explosions at transformers.
When assessing the severity and probability of manifestation of these risk factors, the age of 20 kV power substations is also taken into account, an age that amplifies the accidental potential of electrical equipment.

2. Work load:

Work load of the service and repair team is to:
- *technical revisions (TR) – annually on all equipment in the power substations;*
- *current revisions (RC) – changes in sub-assemblies, replacement of power substation components;*
- *accidental interventions – in the event of faults or failures in primary equipment;*
- *maintenance of auxiliary installations;*
- *maintenance work on the power substation;*
- *changes of lighting fittings.*
Risk factors specific to the work load:
- failure to properly prepare and/or fail to comply with the required steps in the performance of maintenance activities;
- failure to comply with measures to ensure the working area;

- oversized physical effort when removing the cutting-off switches from the switchgears.

3. Performer:

The primary service-repair team for equipment is composed of electricians who are led by a master.

Risk factors specific to the performer:

- *wrong action:* misidentification of the installations in which work is being carried out; wrong maneuvers when performing operational tests; exceeding proximity distances when transporting materials towards the work area and during work; displacements, stationing in hazardous areas outside the working area; falling from the same level by unbalancing, during the transport of materials within the area of the power substation.

- *omissions:* non-use of personal protective equipment as provided or use of non-certified personal protective equipment.

4. Work environment:

Service activity – primary equipment repair is carried out in the external power substation and very rarely in the mechanical room.

Risk factors specific to the work environment:

- *physical risk factors:* inhalation of noxious during in paint work; bad weather conditions (high/low temperature, wind).

Table 5. **Workplace assessment sheet 20 kV Primary Circuit Maintenance**

NATIONAL POWER SECTOR		ASSESSMENT SHEET OF WORKPLACE		NUMBER OF EXPOSED PERSONS		
RESPONSIBLE NATIONAL COMPANY						
20 kV PRIMARY CIRCUIT MAINTENANCE				EXPOSURE TIME: hours/shift		
				ASSESSMENT TEAM:		
The composition of the work system	Identified risk factors	Concrete form of manifestation of risk factors	Maximum foreseeable consequence	Class of severity	Class of probability	Risk level
MEANS OF PRODUCTION	Mechanical risk factors: - functional movements of technical - machinery and hazardous surfaces	1. Traveling by means of transport to the workplace – road accident	DEATH	7	2	2
		2. Accidents caused by the omission of the MR spring during the adjustment operation (the MRI actuator of the 20-20 kV circuit breaker)	3st degree Disability	4	2	3

		3. Cutting edges, sting when replacing broken insulators, TT, TC and damaged discharge devices	Temporary Work Incapacity 3–45 days	2	4	2
		4. Hazard of explosion TRBO transformers	DEATH	7	2	2
	Thermal risk factors	5. Injury by the thermal effect of the electric arc of service and repair personnel when traveling on the territory power substations of the work load	1st degree Disability	6	4	3
	Electrical risk factors: indirect touch	6. Touching of accidentally live metal parts under the conditions: - damage to insulation from the metal housing; - failure of the protective connection	DEATH	7	4	3
WORK LOAD	Inadequate content in relation to security requirements	7. Adequate preparation and/or non-compliance with mandatory steps and measures to secure the work area	DEATH	7	3	3
	Under/oversized workload in relation to the capacity of the performer	8. Dynamic, static effort, forced working positions at ground and height when handling and replacing subassemblies and components of equipments, insulating replacement	Temporary Work Incapacity 45–180 days	3	4	3
WORK ENVIRONMENT	Physical risk factors	9. Inhalation of toxic dust and gases in the execution of the operations of painting	Temporary Work Incapacity 45–180 days	3	2	2

PERFORMER	Wrong actions	10. Incorrect identification of the installations in which they work, wrong maneuvers when performing functional tests	DEATH	7	4	3
		11. Entering the work area unprepared for work safety	DEATH	7	4	3
		12. Incomplete work permit without specifying all working area insurance conditions	DEATH	7	4	3
		13. Exceeding the distances of materials to the work area and during the works	DEATH	7	3	3
		14. Journeys, stationing in hazardous areas outside the working area	DEATH	7	3	3
		15. Falling to the same level through imbalance during the transport of materials to the power substation	Temporary Work Incapacity 3–45 days	2	3	2
	Omission	16. Not using the personal protective equipment provided or use of personal protective equipment non-certified	DEATH	7	3	3

The global risk level at workplace: 20 kV Primary Circuit Maintenance

$$N_{20kV} = \frac{\sum_{i=1}^{16} R_I \cdot r_i}{\sum_{i=1}^{16} r_i} =$$
$$\frac{5 \cdot (2 \cdot 2) + 11 \cdot (3 \cdot 3)}{5 \cdot 2 + 11 \cdot 3} = \frac{119}{43} = \mathbf{2,76} \tag{6}$$

2.5. Risk level assessment for activity: 20 kV Secondary Circuit Maintenance

The team of revisions-repairs of equipments and secondary circuits and prophylaxis have as object of activity: *revision; maintenance; repair of secondary protection and circuits; prophylaxis of power installations.*

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1. Means of production: 20 kV Power Substation:

Risk factors specific to the means of production:
- *electrical risk:* direct contact (unprotected terminals, unprotected heating elements); indirect contact (housing, metal parts).
- *mechanical risk:* functional movements of technical equipments; displacements under the effect of propulsion.
- *thermal risk:* flames, explosion of molten metal particles.

2. Work load:
- *protection checks:* during the revisions, all the verifications provided by the technical books of protection are performed; the monitoring of the protection system parameters is done from the 20 kV control room.
- *measurements and verifications performed by the secondary equipments revisions-repair team:*
• at the internal service panels: checking the electrical connections; measurements at internal service cables; measurements at internal service transformers; checking switching devices and current transformers; calibration of fuses on all circuits; checking the ground connections.
- *within the prophylaxis program of the primary equipment from the 20 kV power substations, the following verification are performed:*
• measurements and checks performed on voltage measuring transformers are: measuring the insulation resistance of the windings; measuring the tangent of the dielectric loss angle at the main insulation; measuring the ohmic resistance of the windings; raising the idling characteristic; measuring the secondary load.
• measurements and checks performed on the current measuring transformers are: measuring the insulation resistance of the windings; measuring the tangent of the dielectric loss angle at the main insulation; measuring the ohmic resistance of the windings; raising the idling characteristic; measuring the secondary load; checking the polarity of the windings.
• measurements and checks performed on the circuit breakers are: measuring the insulation resistance; checking the contact resistance; checking the ohmic resistance of the triggering and triggering coil; low voltage operation of the control and automation installation; checking the dielectric strength of the oil.
• measurements and checks performed at power cables are: checking the continuity and identifying the phases; measuring the insulation resistance.

Risk factors specific to the work load:
- psychic stress on decisions in circuit and scheme modification operations in relation to the consequences of mistakes in performing these operations;
- physical strain, forced working positions during check at the clamp strings.

3. Performer:
The team consists of electricians and a team leader ao foreman who are authorized in terms of OHS (groups I, II, III, IV, V).

Risk factors specific to the performer:

- *wrong actions:* touching the current paths during the high voltage tests; touching a point of the current paths; touching the terminals of devices, strings of clamps, relays; parking, hazardous movements.

- *omissions:* non short circuiting of the secondary windings at the current transformers for carrying out works related to low voltage circuits; non short circuiting of the secondary terminals of the current transformers when opening the current circuits for mounting or dismounting the measuring devices; omission of the connection to the null busbar of the internal services of a conductor from the protection circuit to the own busbar; non use and/or non verification of personal protective equipments.

4. Work environment:

Revisions – repairs of primary equipments and secondary circuits.

Risk factors specific to the work environment:

- *physical risk factors:* lighting.

Table 6. **Workplace assessment sheet 20 kV Secondary Circuit Maintenance**

NATIONAL POWER SECTOR **RESPONSIBLE NATIONAL COMPANY** **20 kV SECONDARY CIRCUIT MAINTENANCE**		**ASSESSMENT SHEET OF WORKPLACE**		**NUMBER OF EXPOSED PERSONS** **EXPOSURE TIME: hours/shift** **ASSESSMENT TEAM:**		
The composition of the work system	**Identified risk factors**	**Concrete form of manifestation of risk factors**	**Maximum foreseeable consequence**	**Class of severity**	**Class of probability**	**Risk level**
MEANS OF PRODUCTION	Mechanical risk factors: movement under dynamic effect	1. Traveling by means of transport to the intervention area – road accident	DEATH	7	1	3
	Electrical risk factors: direct touch	2. Explosions of primary equipment, during the movement on the 20 kV substation territory to perform service attributions	DEATH	7	1	3
		3. Touching unmarked terminals and installations	DEATH	7	1	3

		4. Touching 20 kV busbar during revisions or repairs	DEATH	7	1	3
	– indirect touch	5. Touching of accidentally energized metal parts under the conditions of: - insulation failure; - damage to the protective circuit by grounding; - failure to operate the protection or within the time period before the protection is activated.	DEATH	7	1	3
	Thermal risk factors: flame, explosion of molten metal particles when producing electric arc	6. The capture of personnel by the thermal effect of the electric arc at failure of insulation of primary equipment	1st degree Disability	6	1	3
WORK LOAD	Oversize load in relation to performer's capacity: - psychic stress	7. Psychic stress on decisions in circuit and scheme modification operations in relation to the consequences of mistakes in performing these operations	Territorial Labour Inspectorate 3–45 days	2	2	2
	- physical stress	8. Physical strain, forced working positions during check at the clamp strings.	Temporary Work Incapacity 3–45 days	2	2	2
WORK ENVIRONMENT	- lighting	9. Lighting level in the 20 kV power substation	Temporary Work Incapacity 3–45 days	2	3	2
PERFORMER	Wrong actions:	10. Confusion when working	DEATH	7	1	3

defective execution of operations	on the clamp string in the protection system, resulting in loss of the current transformer secondary circuit, clamp and current transformer terminal overvoltage, electrical shock hazard, transformer failure and untimely equipment tripping				
	11. Touching of current paths-conductors, clamps or test machine busbars during high voltage tests, electrical shock hazard	DEATH	7	1	3
	12. Not short circuit of secondary windings at current transformer for carrying out works related to low voltage circuit – hazard of electric shock	DEATH	7	1	3
	13. Touching the terminals of devices, clamps, relays, during voltage checking of secondary circuits under the use of damages personal protective equipment	DEATH	7	1	3
	14. Not short circuit of the secondary	DEATH	7	1	3

		terminals of current transformer when opening current circuits for mounting / dismounting measuring devices				
	Parking, hazard movings	15. Parking or moving outside the work area or outside normal routes	DEATH	7	1	3
	Omission	16. Non use and/or non verification of personal protective equipments.	DEATH	7	1	3

The global risk level at workplace: 20 kV Secondary Circuit Maintenance

$$N_{EP} = \frac{\sum_{i=1}^{17} R_I \cdot r_i}{\sum_{i=1}^{17} r_i} = \frac{13 \cdot (3 \cdot 3) + 3 \cdot (2 \cdot 2)}{13 \cdot 3 + 3 \cdot 2} = \frac{129}{45} = \mathbf{2,87} \tag{7}$$

2.6. Global risk level assessment of the 400/220/110/20 kV power substation

The risk levels, determined for each workplace in the 400/220/110/20 kV power substation are generally the followings:

Table 7. **Workplace from 400/220/110/20 kV power substation**

No.	WORKPLACE	LEVEL RISK (N_{rp})
1	400 kV, 220 kV and 110 kV Operational service	2,28
2	20 kV Operational service	3
3	400 kV, 220 kV and 110 kV Primary circuit maintenance	2,78
4	20 kV PRIMARY Circuit maintenance	2,76
5	20 kV Secondary circuit maintenance	2,87

The global risk level of the 400/220/110/20 kV power substation is:

$$N_{rg} = \frac{\sum_{p=1}^{n} r_p \cdot N_{rp}}{\sum_{p=1}^{n} r_p} =$$

$$\frac{(2,28 \cdot 2,28) + (3 \cdot 3) + (2,78 \cdot 2,78) + (2,76 \cdot 2,76) + (2,87 \cdot 2,87)}{2,28 + 3 + 2,78 + 2,76 + 2,87} = \frac{37,75}{13,69} = 2,75 \tag{8}$$

$$\mathbf{N_{rg\text{-power substation}} = 2,75}$$

3. CONCLUSIONS

After the OHS risk analysis, the following conclusions are generated: global risk level of the 400/220/110/20 kV Urechesti power substation was calculated **2,75 – low – very low risk,** the operative staff of the 400/220/110/20 kV Urechesti power substation complies with the occupational safety and health norms, the maintenance staff of the 400/220/110/20 kV Urechesti power substation complies with the occupational safety and health norms, the danger of injury and professional illness is very low, and the entire 400/220/110/20 kV Urechesti power substation works correctly and does not show OSH non-conformities and does not pose a danger to the National Power System.

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CONTRIBUTIONS REGARDING CONSTRUCTION SOLUTIONS FOR POWER SUBSTATIONS – ESSENTIAL ELEMENTS OF THE NATIONAL CRITICAL INFRASTRUCTURE

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Abstract: Power substations represent indispensable nodes within the National Critical Infrastructure, ensuring the continuity, stability, and resilience of National Power System. This study presents a set of contributions aimed at improving construction solutions for modern power substations, with a focus on structural reliability, operational safety, and adaptability to emerging technological and environmental challenges. By analyzing current design standards, material performance, and construction practices, the research identifies key vulnerabilities and proposes optimized configurations that enhance physical protection, reduce maintenance requirements, and support advanced monitoring and control systems. The proposed solutions integrate principles of robust engineering, risk mitigation, and lifecycle sustainability, ultimately contributing to the strengthening of national power security. The findings offer practical guidance for engineers, policymakers, and infrastructure planners involved in the development and modernization of power substations within critical national frameworks.

Keywords: power substation, national critical infrastructure.

1. INTRODUCTION

Power substations represent indispensable nodes within modern power networks, serving as the primary interface for voltage transformation, system protection, and power flow control. Their technical and operational significance places them among the essential components of national critical infrastructure, with direct implications for economic stability, public safety, and social well-being [2], [25], [28], [31]. As energy systems become increasingly complex – driven by rising demand, the

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integration of renewable resources, and the digitalization of grid operations – the construction of robust, secure, and adaptable substations has emerged as a strategic priority for infrastructure planners and policymakers [1], [3], [20].

Recent disruptions caused by extreme weather events, aging assets, cyber-physical threats, and population-density shifts underscore the need to reassess conventional construction approaches. Traditional substation designs, while proven and widespread, often lack the flexibility and resilience required to withstand evolving threats and performance expectations [4], [26], [29], [32]. Consequently, research on innovative construction solutions – ranging from advanced structural materials and modular architectural layouts to enhanced protection systems and smart monitoring technologies – is becoming increasingly relevant [14]. These solutions aim not only to extend the operational lifespan of substation infrastructure but also to elevate its resilience against natural hazards, technical failures, and malicious attacks [15], [17].

In this context, contributions to the field of substation construction design are vital for national energy security strategies. Improved construction methodologies can mitigate vulnerabilities by enhancing structural integrity, facilitating rapid restoration after disturbances, and ensuring continuity of service across interconnected grid components [16], [22], [27]. Moreover, the adoption of standardized construction practices and modern engineering solutions supports better coordination between utility operators, regulators, and emergency response agencies. Such developments are essential for establishing a reliable and secure energy system capable of supporting critical services such as healthcare, transportation, communications, and industrial production [8], [21], [30], [35].

This study examines recent advancements and practical contributions regarding construction solutions for power substations, emphasizing their role within the broader framework of national critical infrastructure protection [6], [33], [36]. By evaluating current challenges, emerging technologies, and best-practice engineering approaches, the analysis aims to offer insights that can inform future design, planning, and policy decisions. Ultimately, strengthening the construction and resilience of power substations contributes not only to the technical robustness of the electrical grid but also to the overall resilience and sustainability of national infrastructure systems [5], [7], [23].

2. CONSTRUCTIVE SOLUTIONS FOR POWER SUBSTATIONS

2.1. Overview

The constructive solutions for the construction of HV, VHV and UHV power substations must satisfy a series of general conditions regarding the transmission and distribution of electricity in conditions of quality and economic efficiency, strictly respecting the requirements regarding: [8], [10], [24].
- *occupational health and safety;*
- *installations security (facility);*
- *security and environmental protection.*

The priority of the criteria has changed significantly in recent years.

Fundamentally, technology has long been considered the primary and driving force in design, and the economy has taken second place, taking into account, more or less, the criterion of the environment [9], [16], [23].

Now and in the future, the safety and health at work of the operational staff, the security of the installations / facilities and the environment, occupy the key positions, with the economic criterion on the second position [34], [37].

Conditions related to the installation voltage:

Table 1. **Insulation levels associated with the highest voltages for equipment in networks with nominal voltages $U_n \geq 110$ kV**

Nominal voltage kV	The highest voltage of the equipment kV	Nominal holding voltages					
		At the lightning impulse kV_{max}		At the switching impulse kV_{max}		At industrial frequency kV	
		A	B	A	B	A	B
110	123	550	450	(440)	(360)	230	185
220	245	1050	950	(750)	(650)	460	395
400	420	1425	1425	1050	1050	-	-
765	787	2100	2100	1425	1425	-	-

In *Table 1.* columns *A* indicate the values used for all equipment, except for the power transformers for which the values in column *B* are provided.

The values in parentheses refer to installations in which the insulation coordination study indicates the possibility of switching overvoltages with a risk of defect greater than 10^{-4}.

For the safety of the personnel who carry out the current operation of the installation or the repairs and overhauls, the minimum allowed distances that must be ensured by the construction of the power substation are normed [19], [12].

Table 3. **Minimum distances allowed for the protection of persons who may be in the area of a power substation**

Symbol of the minimum distance	Calculation relationship	Values of the minimum permissible distances, in mm, for networks with nominal voltages			
		110 kV	220 kV	400 kV	765 kV
B_1	$A_0 + 30$	930	1830	3130	5530
B_2	$A_0 + 100$	1000	1900	3200	5600
B_3	$A_0 + 750$	1650	2550	3850	6250
C	$A_0 + 2500$	3400	4300	5600	8000
D	$A_0 + 1250$	2150	3050	4350	6750
E	$A_0 + 600$	1500	2400	3700	6100
F	A_0	900	1800	3100	5500
G	$A_0 + 1500$	2400	3300	4600	7000
H	-	6000	7000	8000	10000

2.2. Types

Constructive types of power substations: [1], [8]
- by voltage level :
  - *HV (high voltage): 50 kV – 110 kV;*
  - *VHV (very high voltage): 110 kV – 400 kV;*
  - *UHV (ultra high voltage): 400 kV – 1100 kV.*

- by insulating material :
  - *with air insulation – AIS (Air Isulated Substation): 50 kV – 1100 kV;*
  - *with gas insulation – GIS (Gas Insulated Substation): 52 kV – 1100 kV;*
  - *hybrid (air-gas) – HIS (Hybrid Insulated Substation): 145 kV – 550 kV.*

2.3. Power substations with air insulation – AIS (Air Insulated Substation)

The most important element in the construction of an power substation with the insulation in the air is *the monofilar (single line) scheme.*

The wiring diagram of an power substation with air insulation obviously influences the constructive solution, first of all by the *number of equipment* it contains and the *connections* it makes.

There are schemes that, for example, have a small number of circuit breakers, so fewer separators (in a high, very and ultra high voltage installation, a circuit breaker must be flanked by separators or similar separation elements).

There are schemes with a large number of switches (for example, two on each circuit), so with many separators [18].

Separators greatly influence a constructive solution of an external type power substation.

Another element of the wiring diagram that greatly influences the construction solution is the *number of busbars* of an power substation with air insulation.

In addition to the surface occupied by the busbars, the way of connecting the busbars of each circuit is a problem that must be solved because it involves several separators and a certain way of access of the connections to their terminals.

There are other elements of the wiring diagram that influence the constructive solution, such as, for example, *the total number of circuits of the power substation* , the *provision of the possibility of bypassing the switch* , the *number of coupling circuits* , the *use of combined torques,* etc.

Depending on the single-wire scheme, the following types of power substation can be built: [11], [13].
- *power substations with busbars;*
- *power substations without busbars.*

In turn, power substations with busbars are divided into:
- *power substations with single busbars;*

- *power substations with double busbars;*
- *power substations with triple busbars;*
- *power substations with transfer bars.*
  The single busbars power substation has only 1 circuit breaker.
  Power substation with double busbars are divided into:
- *double busbars with 1 circuit breaker;*
- *double busbars with 1,5 circuit breakers;*
- *double busbars with 2 circuit breakers.*

  Power substations without busbars are divided into:
- *polygon type power substations (ring);*
- *H – power substations (upper H and lower H).*
  Air-insulated power substations can operate at the following voltages:
- *50 kV - 1100 kV.*

2.3.1. Wiring diagrams with busbars

Schemes with a busbar system:
Diagram with a busbara system with 1 CB - circuit breaker

Name / Distribution scheme	Legend	Nominal voltages
1 Busbars - 1 CB / CIRCUIT	W - busbars; Q_1 - Q_3 – circuit breakers; S_1 - S_3 – separators.	110 kV
This circuit has a simple busbars, and all circuits are connected directly to the busbar. A single malfunction at the busbars will cause an interruption of the entire system. Maintenance on the busbars would require decoupling the entire system. Low reliability of the power substation, this type of power substation is not		

recommended where the availability is very high.

Schemes with two busbars systems:

Diagram with two busbars systems with 1 CB - circuit breaker

Name / Distribution scheme	Legend	Nominal voltages
2 Busbars - 1 CB / CIRCUIT 	W1, W2 - busbars; Q_1 - Q_3, - circuit breakers; S_1 - S_8 - separators;	400 kV 220 kV 110 kV
This scheme has two busbars systems. Each circuit has its circuit breaker and by closing or opening the busbars separators the circuit can be switched to one of the two busbars. The transition from one busbars to another is performed by means of the transverse coupling, from where the corresponding switch and the two busbars separators are actuated. Low reliability of the power substation.		

Diagram with two busbar systems with 1,5 CB - circuit breakers

Name / Distribution scheme	Legend	Nominal voltages
2 Busbars – 1,5 CB / CIRCUIT	W1, W2 - busbars; Q_1 - Q_6 – circuit breakers; S_1 - S_{16} - separators; T - power transformers; LEA - Overhead	1100 kV 750 kV 400 kV

	Power Lines	
This type of scheme is of interest in the case of circuits for which a very high safety in operation must be ensured. A way to reduce investment, applied in the case of very high voltage power substations, is the use of three circuit breakers for two circuits. However, the high cost of achieving protections and quick automatic reconnection remains a disadvantage, as the middle switch must operate independently in each of the directions of the two departures. The technical-economic calculations show that such schemes can be economically efficient especially when: - the duration of non-delivery of energy, as a result of overhaul / repair works in power substations is long; - the electric load carried on the circuits is high (usually in stations with $U_n \geq 220$ kV); - there is a high sensitivity to interruptions of the supplied areas and the circuits are not reserved by other supply routes.		

Diagram with two busbar systems with 2 CB - circuit breakers

Name / Distribution scheme	Legend	Nominal voltages
2 Busbars - 2 CB / CIRCUIT	W1, W2 - busbars; Q_1 - Q_4, - circuit breakers; S_1 - S_4 - separators;	1100 kV 750 kV 400 kV
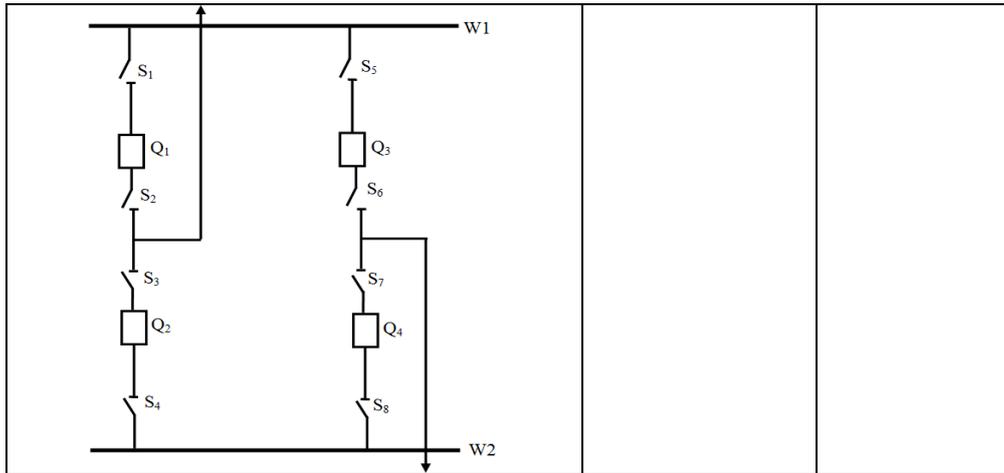
Great flexibility in service and increased availability, because:
- in normal operation, both busbars systems are kept energized; all circuit breakers are made by switches, which reduces the risk of serious damage (accompanied by free electric arc);
- each busbars can be insulated for maintenance purposes without interrupting any circuit; an incident on a busbars system does not affect any circuit, so it does not lead to power outages;
- the overhaul / repair work on the power cells can be performed without interrupting the operation of the respective circuit, so without damage to the delivery;
- due to the advantages mentioned above, the supply interruption time and the undelivered power are considerably reduced, no additional transverse coupling and bypass circuits being necessary;
- the main disadvantage of such schemes is the increase in investments for the equipment of power substations, both due to the increased number of circuit breakers and as a result of higher costs for providing protection.

Schemes with three busbar systems:
Diagram with three busbar systems with 1 CB - circuit breaker on the circuit

Name / Distribution scheme	Legend	Nominal voltages
3 Busbars – 1CB / CIRCUIT	W1, W2, W3 - busbars; Q_1 Q_2 – circuit breakers; S_1 - S_6 - separators;	110 kV 220 kV

This scheme has three busbars systems.

Each circuit has its circuit breaker and by closing or opening the bar dividers the circuit can be switched to one of the three busbars.

The transition from one busbars to another is performed by means of busbars separators.

Low reliability of the power substation.

Schemes with transfer busbars:
Diagram with double busbars system, U-linking of bars, with transfer bars

Name / Distribution scheme	Legend	Nominal voltages
MAIN COLLECTOR BUSBARS AND TRANSFER COLLECTOR BUSBARS 	Scheme composition: W_1 - main busbars; W_2 - transfer busbars; Q_1, Q_3, - circuit breakers; S_1, S_8, - separators;	400 kV 220 kV
When maintenance work is required, the transfer busbars are supplied by closing the circuit breaker Q_2, and the separators S_4 and S_5. In this way both circuits remain voltage during maintenance. This scheme is slightly more expensive than the single busbars scheme, as additional switches and separators are involved.		

2.3.2. Wiring diagrams without busbars
Polygon scheme (ring)

Name / Distribution scheme	Legend	Nominal voltages
SCHEME WITH POLYGONAL SYSTEM, WITHOUT COLLECTOR BUSBARS	Q_1 - Q_4 – circuit breakers; S_1 - S_{12} - separators; T_1, T_{12} - power transformers; LEA_1, LEA_2 - Overhead Power Lines.	1100 kV 750 kV 400 kV 220 kV

The power substation has no busbars.

Due to the closed contour, although a circuit has only one switch, the scheme has the advantages of connecting each connection to the network through two switches, this leads to greater flexibility, especially in terms of switch maintenance, with lower costs than in in the case of the schemes presented:
- all circuit breakers are made by switches which reduces the risk of serious damage (accompanied by free electric arc);
- disconnection / tripping of any circuit breaker is done without interrupting the load on the circuit, so it is not necessary to provide a bypass system;
- the transverse connections between the nodes are ensured by the sides of the polygon (equipped with switches), so a transverse coupling circuit is useless.

Among the disadvantages of polygonal schemes can be mentioned:
- higher amperage for circuit breakers, each serving two electrical circuits; in this respect, the scheme is more indicated at $U_n \geq 220$ kV;
- higher volume of protections and more complicated secondary circuit schemes;
- polygonal diagrams are an important alternative to diagrams with 1,5 circuit breakers for the realization of connection diagrams to very high voltage and ultra high voltage power stations (for example, the 750 kV substation from Isaccea is "a square").

Scheme H - superior

Name / Distribution scheme	Legend	Nominal voltages
SCHEME WITH TYPE H SYSTEM - SUPERIOR, WITHOUT COLLECTOR BUSBARS	Q_1 - Q_3 – circuit breakers; S_1 - S_4 - separators; T_1, T_2 - power transformers; LEA_1, LEA_2 - Overhead Power Lines.	1100 kV 750 kV 400 kV 220 kV

The power substation has no busbars.

The name comes from the resemblance of the connection scheme with the letter (capital letter H), the scheme being obtained by connecting two cells block power line - power transformer through a bridge (longitudinal coupling).

The diagram shows an increased availability compared to DCP (deep connection power substations) with two line block power cells-transformer, because in case of unavailability of a circuit in the block structure, the operation of the power substation can continue with the remaining elements, through the bridge (coupling).

In the case of scheme H above, the coupling / decoupling maneuvers of a transformer circuit are performed directly, by switching a single switch and therefore involve a smaller number of operations than the maneuvers corresponding to the coupling / decoupling of a line circuit.

Scheme H - lower

Name / Distribution scheme	Legend	Nominal voltages
SCHEME WITH H TYPE SYSTEM - LOWER, WITHOUT COLLECTOR BUSBARS 	Q_1 - Q_3 – circuit breakers; S_1 - S_9 - separators; T_1, T_2 - power transformers; LEA_1, LEA_2 - Overhead Power Lines.	1100 kV 750 kV 400 kV 220 kV
The power substation has no busbars. - the name comes from the resemblance of the connection scheme with the letter (capital letter H), the scheme being obtained by connecting two power cells block power line -		

power transformer through a bridge (longitudinal coupling);
-   the diagram shows an increased availability compared to DCP (deep connection power substations) with two line block power cells-transformer, because in case of unavailability of a circuit in the block structure, the operation of the power substation can continue with the remaining elements, through the bridge (coupling);
-   in the case of the lower diagram H, the coupling / decoupling maneuvers of a line circuit are performed directly, by switching a single switch, while the maneuver of overhauling a transformer circuit involves five successive operations.

3. CONCLUSIONS

Air-insulated power substations (AIS) remain one of the most widely used substation types worldwide due to their robustness, simplicity, and cost-effectiveness.

As power systems expand and requirements for reliability, safety, and environmental sustainability increase, contributions to improving construction solutions for AIS are critically important.

Their significance can be summarized in several key areas: **Enhancing System Reliability and Operational Safety:** Construction solutions directly influence the mechanical strength, seismic resilience, and fault performance of the substation, improved designs help reduce outages, improve fault isolation, and increase system uptime, and optimized layouts and clearances enhance personnel safety by minimizing flashover and arc-risk scenarios. **Reducing Construction Time and Cost:** Innovative construction methods – modular foundations, prefabricated structures, or optimized steelwork – lower material costs and reduce site labor, and ell-engineered civil solutions decrease rework, delays, and long-term maintenance costs.

Adapting to Space and Environmental Constraints: Urbanization and land scarcity require more efficient substation footprints, and contributions to compact AIS layouts, optimized bus configurations, and elevation strategies allow installations in constrained areas without sacrificing reliability. **Supporting Grid Modernization and Increased Load Demand:** Upgraded construction solutions accommodate higher short-circuit levels and increased load flow due to grid expansion, renewable integration, and electrification, and improved designs facilitate future scalability and equipment replacement without major civil redesigns.

Improving Resilience Against Environmental and Climatic Stress: AIS construction must withstand extreme temperatures, lightning, pollution, humidity, and environmental corrosion, and engineering advancements – improved grounding systems, better drainage, anti-corrosion materials, and enhanced insulation clearances – significantly boost long-term performance.

1. **Ensuring Compliance with Evolving Standards:**
-   Contributions help align AIS construction with modern standards (IEC, IEEE, national codes), and this ensures legal compliance, safe operation, and harmonization with international best practices.

Supporting Sustainability and Environmental Stewardship: New construction solutions can reduce land use, limit ecological disturbance, and incorporate environmentally responsible materials, and life-cycle-based design choices help minimize waste and reduce carbon footprint over the substation's lifespan.

Advancing Technological Integration: Modern AIS facilities must integrate digital monitoring, SCADA systems, and condition-based maintenance, and contributions in civil and structural design support better cable routing, control building optimization, and electromagnetic compatibility.

Contributions to the construction of air-insulated power substations are important because they directly influence *safety, reliability, cost efficiency, environmental performance, and the long-term sustainability of electrical power systems*. As grid demands grow, innovative construction solutions are essential for ensuring that AIS substations continue to meet modern operational needs.

Strategy for Air-Insulated Power Substations (AIS):

1. Strategic Planning & Site Selection

Objectives: reliability, safety, maintainability, future expansion Key considerations:

- Location: Adequate land area (AIS typically requires more space than GIS), low environmental risk (flooding, pollution, corrosive atmospheres), proximity to load centers and transmission corridors, regulatory compliance: environmental permits, right-of-way, zoning, and grid integration studies: short-circuit levels, load flow, stability, protection coordination.

2. System Architecture & Layout Strategy

Design principles for AIS layouts: Clear segregation of bays (line, transformer, bus couplers, etc.), and busbar configuration: choose based on reliability vs. cost.

- ➢ Single bus (simple, low cost);
- ➢ Double bus (higher reliability);
- ➢ One-and-a-half breaker scheme (high reliability, high cost).

Safety clearances: follow standards such as IEC 61936-1 or IEEE C37 series, and future expansion: allocate land for additional bays, feeders, or voltage levels.

3. Equipment Strategy

AIS equipment includes: Circuit breakers (SF6-based or vacuum technology at lower voltages), disconnect switches and earthing switches, instrument transformers (CTs, VTs), busbars and insulators, power transformers, and surge arresters.

Strategic selection considerations:

- Reliability ratings and environmental performance;
- Availability of spare parts;
- Vendor diversity to avoid single-sourcing risks;
- Standardization across substations for easier maintenance.

4. Protection, Control, and Automation Strategy

- Protection schemes: distance, differential, overcurrent, busbar protection, transformer protection;
- Redundancy: dual protection channels (A/B systems);
- SCADA/EMS integration: IEC 61850-based systems preferred for modularity.
- Cybersecurity: role-based access, network segmentation, encryption, monitoring.

5. Construction & Commissioning Strategy

- Phased execution: minimize grid interruptions;

- Factory Acceptance Tests (FAT) for all primary and secondary equipment;
- Site Acceptance Tests (SAT): insulation checks, functional tests, protection tests;
- Commissioning plan: clear sequencing, risk assessments, fallback procedures.

6. Operations & Maintenance Strategy
- Preventive maintenance schedule:
- ➢ Breaker inspections;
- ➢ Insulator cleaning;
- ➢ Thermographic monitoring;
- ➢ Transformer oil testing.
- Condition-based monitoring: partial discharge monitoring, vibration sensors, SCADA analytics;
- Spare parts strategy: critical spares onsite (breaker mechanisms, CTs, relays);
- Training: annual operator training, simulation of protection events.

7. Reliability & Resilience Strategy
- Redundant paths: avoid single-point failures in busbars and feeders;
- Switching procedures: standardized to reduce human error;
- Emergency restoration: mobile substations, transformer sharing agreements;
- Climate resilience: lightning protection, storm-hardening structures, flood mitigation.

8. Environmental & Sustainability Strategy
- Minimize SF6 leakage (if SF6 breakers are used);
- Explore SF6-free technologies (air-blast or vacuum interrupters for appropriate voltage levels);
- Noise mitigation from transformers and breakers;
- Proper disposal plans for oils, insulators, and metals.

9. Lifecycle & Financial Strategy
- CAPEX vs. OPEX evaluation (AIS is cheaper upfront than GIS but takes more space);
- Lifecycle cost analysis: equipment aging, modernization intervals;
- Standardization: reduces cost and simplifies training;
- Digital twin modeling to optimize maintenance and upgrades.

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CONFIGURATION AND FUNCTIONALITY OF PRIMARY CIRCUITS IN POWER TRANSMISSION SUBSTATIONS – AN APPROACH TO CRITICAL ENERGY INFRASTRUCTURE

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Abstract: The reliable operation of power transmission substations is fundamental to the stability and security of modern electric power systems. This study examines the configuration and functionality of primary circuits within transmission substations, emphasizing their role as critical energy infrastructure. Key components, including busbars, circuit breakers, disconnectors, transformers, and protection systems, are analyzed to elucidate their operational interactions and fault management capabilities. The research also explores common substation topologies – single bus, double bus, ring bus, and breaker-and-a-half schemes – highlighting their respective advantages and vulnerabilities in terms of reliability, maintenance, and operational flexibility. By integrating theoretical analysis with practical considerations, this work provides a systematic framework for assessing the resilience of primary substation circuits against disruptions and emphasizes strategies for enhancing energy security. The findings contribute to the optimization of substation design and the development of robust operational practices for critical power transmission infrastructure.

Keywords: primary circuits, power transmission substation, critical energy infrastructure.

1. INTRODUCTION

Power transmission substations constitute a pivotal component of modern electrical energy systems, serving as the critical nodes where electrical energy is transformed, regulated, and distributed to meet varying demand patterns [2], [21], [23], [25]. The configuration and functionality of primary circuits within these substations

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are central to ensuring reliable, efficient, and secure power delivery [22]. Primary circuits, encompassing high-voltage busbars, circuit breakers, disconnectors, transformers, and associated protective equipment, form the backbone of substation operations, providing both the physical and operational pathways through which electrical energy flows from generation sources to distribution networks [1], [3], [16].

The design and configuration of these circuits are influenced by multiple technical, economic, and safety considerations. Factors such as fault tolerance, redundancy, switching flexibility, and maintenance accessibility dictate the arrangement of busbars and the selection of circuit elements. For instance, configurations such as single bus, double bus, or ring bus topologies offer different balances between operational reliability and investment cost, while ensuring that critical loads remain energized during maintenance or fault conditions [13], [27], [30]. Functional performance is further enhanced by integrating automated control systems and protection schemes, which safeguard both the equipment and the network against short circuits, overloads, and transient disturbances [24], [32], [35].

In the context of critical energy infrastructure, primary circuits in transmission substations play a strategic role not only in maintaining continuous power supply but also in supporting national energy security. Disruptions in these circuits can propagate across large geographic areas, leading to cascading failures with substantial economic and social consequences [5], [11], [14]. Consequently, understanding the detailed configuration and operational principles of primary circuits is essential for engineers, planners, and policymakers aiming to enhance grid resilience, optimize maintenance practices, and accommodate emerging energy technologies such as renewable integration and smart grid applications [18], [26], [31].

This study examines the configuration and functionality of primary circuits in power transmission substations, with a particular emphasis on their role as critical energy infrastructure. By analyzing standard circuit arrangements, operational considerations, and protection mechanisms, the research highlights the fundamental principles that ensure the continuity, stability, and safety of power transmission systems [8], [15], [19]. This approach not only underscores the technical complexity of substation design but also situates it within the broader imperative of sustainable and resilient energy systems [4], [6], [17].

2. STRUCTURE AND COMPOSITION OF PRIMARY CIRCUITS

2.1. Power cell

The primary circuits of a power substation contain those elements and equipment that directly carry out the transfer of electricity, or compete directly in carrying out this transfer [28], [33], [36].

The primary circuits of a power substation are physically made in the form of power cells.

The power cell is a component part of an power substation which contains the equipment belonging to a single circuit or to a measuring or protection device and

which constitutes from a functional, constructive point of view and of the space occupied by a distinct unit [10], [12], [29].

In general, the name of the cell is given by the circuit whose elements practically make up the cell.

In primary circuit diagrams, the elements can be grouped into functional cells, often embodied in constructive-functional units: [7], [9], [34]

- *Power Line Arrival / Departure Cells:*
  - Overhead power line – OHL;
  - Cable power line – CPL.
- *Power Transformation Cells:*
  - Power Transformer;
  - Power Autotransformer.
- *Coupling Cells:*
  - Longitudinal;
  - Transversal;
  - Combined.
- *Coil Cells:*
  - Compensation;
  - Reactance;
  - Extinguish.

2.2. Types of power cells

2.2.1. Power Line Arrival / Departure Cells:

- Overhead power line – OHL;
- Cable power line – CPL. [8], [37]
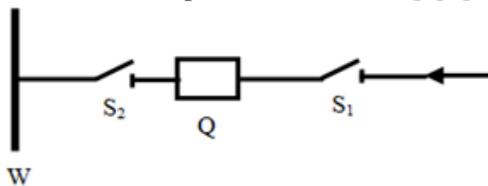
| **Fig.1.** Power line arrival cell | **Fig.2.** Power line departure cell |
| (simple busbars) | (simple busbars) |
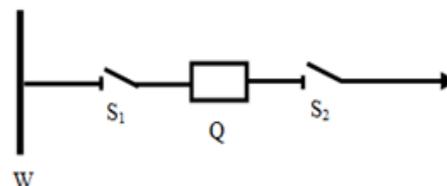
S_1, S_2 - separators; Q – circuit breakers; W - busbars;

The schemes are valid for HV, VHV and UHV;
The energy entered the cells through an OHL, supplies busbars W;
The cells are protected against overvoltages by a discharger;
Low reliability for power substation.

2.2.2. Transformation Cells

- Transformer;
- Autotransformer. [9], [39]
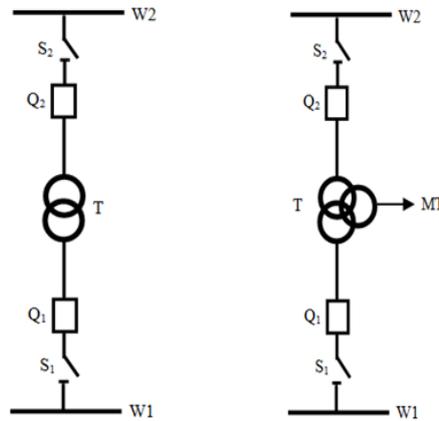
Fig.3. Transformer / autotransformer cells

W1 - 400 kV busbars;   W1 - 400 kV busbars;

W2 - 220 kV busbars;   W2 - 220 kV busbars;

S_1, S_2 - separators; S_1, S_2 - separators;

Q_1, Q_2 – circuit breakers; Q_1, Q_2 – circuit breakers;

T - transformer.   T - transformer, which outputs on the tertiary 20 kV.

2.2.3. Coupling Cells:
- Longitudinal;

- Transversal;

- Combined. [7]

a) Longitudinal coupling type 1 (automatic)
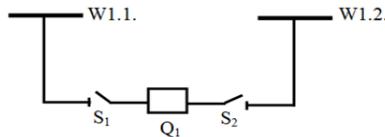
Fig.4. Longitudinal coupling type 1 (automatic)

W1.1. - W1.2. - longitudinally sectioned busbars system; S_1, S_2 - separators; Q_1 – circuit breaker;

It is mainly used in HV, VHV and UHV power substations.

Elasticity and maximum safety in operation are provided by the longitudinal coupling with 2 separators and a switch.

The connection/disconnection of the busbars sections is done in this case only with the help of the switch, capable of extinguishing the electric arc.

The overhaul/repair work on the coupling circuit breaker can be done with the mention of both live busbars sections.

In normal operation, the longitudinal coupling circuit is kept in hot reserve (the coupling separators are closed, the circuit breaker is tripped).

Maintaining the torque in this state has some advantages for the safe operation of the power substation.

To increase the continuity in operation, the longitudinal couplings equipped with switch are provided with automatic reserve locking systems – ASR (automatic start of the reserve).

b) <u>Longitudinal and bypass coupling type 1</u> :
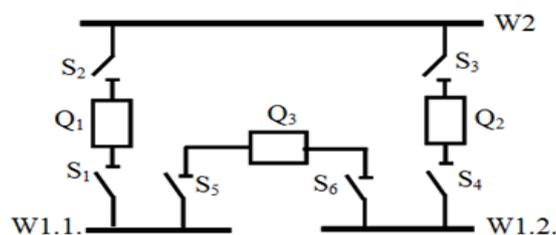
Fig.5. Longitudinal and bypass coupling type 1

W1.1. - W1.2. - double sectioned busbars system; W2. - busbars with bypass;

It is mainly used at HV, VHV and UHV power substations.

In order to increase the continuity in the consumers' supply, the schemes with simple longitudinal sectioned busbars system can be associated with the bypass.

For a high elasticity in the operation of such schemes, corresponding to each node of busbars can be provided individual couplings, one longitudinal and two bypass.

c) <u>Longitudinal and bypass coupling type 2</u> :
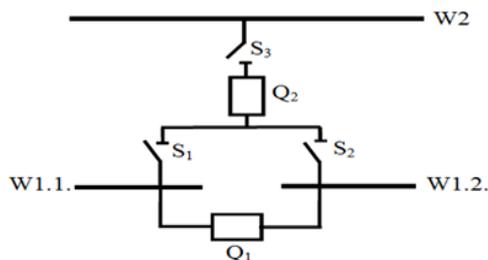
Fig.6. Longitudinal and bypass coupling type 2

W1.1. - W1.2. - double system of longitudinally sectioned busbars; W2. - bypass busbars;
S_1 - S_3 - separators; Q_1 - Q_2 – circuit breakers;

It is mainly used at HV, VHV and UHV power substations.

Under conditions of lower elasticity, the investment effort can be significantly reduced by using multi-function couplings.

By a convenient selection of the busbars separators, with the help of such a coupling, two couplings can be made in turn.

The main disadvantage of using these multi-function couplings is that in case of overhaul or failure of the coupling switch element, all possibilities of coupling the various nodes together are lost [38].

In case of a refusal of the only coupling switch, the whole power substation is disconnected (total interruption), and switching through separators is a potential source of incidents on the busbars, with very serious consequences.

d) Longitudinal and bypass coupling type 3 :
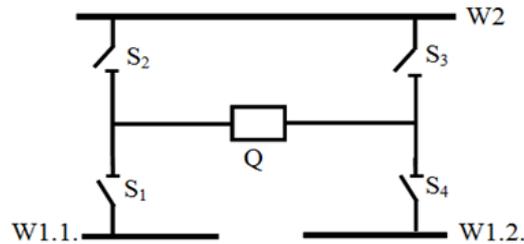
Fig.7. Longitudinal and bypass coupling type 3

W1.1. - W1.2. - double system of longitudinally sectioned busbars; W2. - bypass busbars; S_1 - S_4 - separators; Q – circuit breaker;

It is mainly used at HV, VHV and UHV power substations.

By a convenient selection of the busbars separators, three couplings can be made in turn with the help of such a coupling.

The main disadvantage of using multi-function couplings is that in case of overhaul or failure of the coupling switch, all possibilities of coupling the various nodes together are lost.

In case of a refusal of the only coupling switch, the whole power substation is disconnected (total interruption), and switching through separators is a potential source of incidents on the busbars, with serious consequences.

e) Transverse coupling :
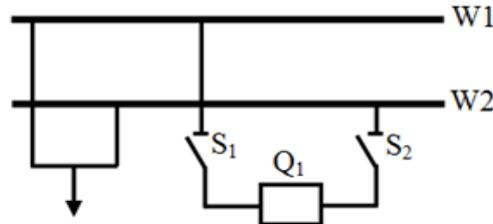
Fig.8. Transverse coupling

W1 - W2 - uncut busbars system; S_1, S_2 - separators; Q_1 – circuit breaker;

It is mainly used at HV, VHV and UHV power substations.

Elasticity and maximum safety in operation are provided by the cross coupling with 2 separators and a switch.

By closing the coupling, consumers have double power, thus increasing the reliability of the power substation.

2.2.4. Coil Cells:
- *Compensation;*
- *Reactance;*
- *Extinguish.* [7], [9]
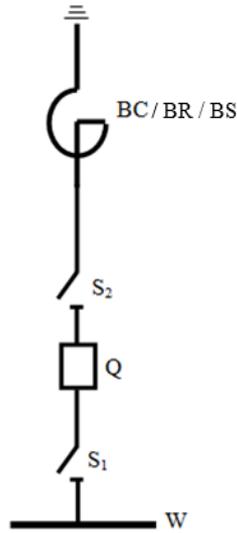
Fig.9. Coil cell
W - busbars; S_1, S_2 - separators; Q – circuit breaker;
BC - compensation coil; BR - reactance coil; BS - extinguishing coil;

It is mainly used at HV, VHV and UHV power substations.
The cell is protected against surge arrester surges

2.3. Busbars

In *figure 10.* the ways of arranging the phases in an power substation are represented.

In the associated phases it can be seen that there are two busbars systems (BC 1, BC 2) with three separate associated phases (R, S, T), in the separate phases there are two busbars systems (BC 1, BC 2) for each phase in part (R, S, T), the phases being separate, and in the mixed phases there are two busbars systems (BC 1, BC 2) for each phase in part (R, S, T), the phases being also associated and separate [9].
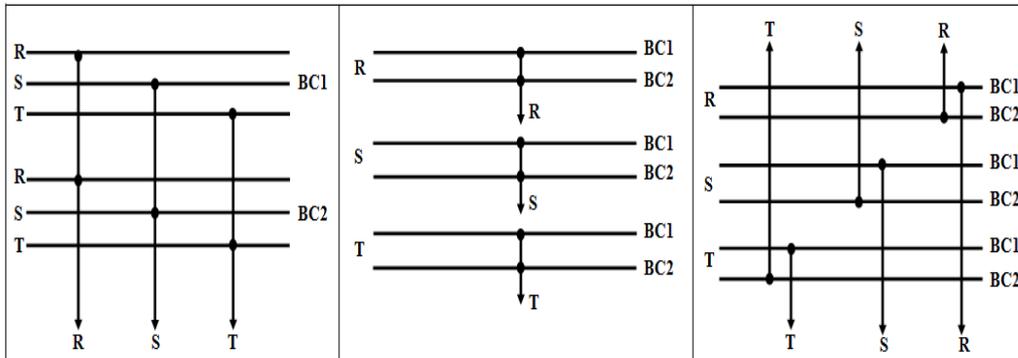
Fig.10. Ways of arranging the phases in an power substation
a - associated phases   b - separate phases   c - mixed phases

2.4. Types of busbars

2.4.1. Simple busbars (not sectioned):
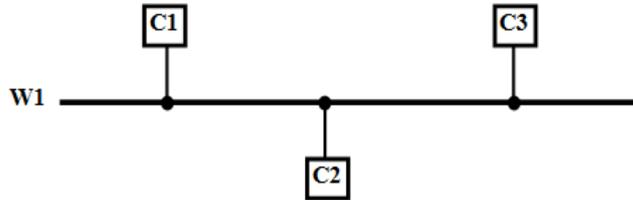
Fig.11. Simple busbars unsectioed
W1 - simple busbars system;
C1, C2, C3 - power cells connected to busbars.

It is used for all voltage levels, minimal investment, very low elasticity in operation and very low reliability of power substations.

2.4.2. Simple busbars longitudinally sectioned:
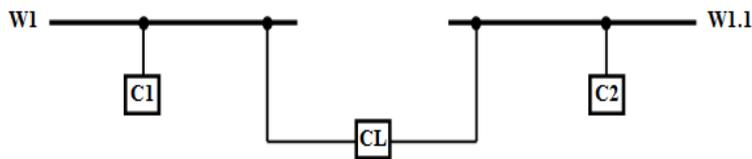
Fig.12. Simple busbars longitudinally sectioned
W1; W1.1. - simple busbars system cut longitudinally;
C1, C2 - electrical cells connected to busbars;
CL - longitudinal coupling.

It is used for all voltage levels, minimum investment, very low elasticity in operation because the coupling / decoupling of the two sections of busbars can be done only in the absence of load (after disconnecting the power supplies).

In case of incorrect maneuvers, both sections of the busbars must be decommissioned.

Each electrical cell is connected to one of the busbars systems (W1 or W2).

2.4.3. Simple cross-sectioned busbars type 1:
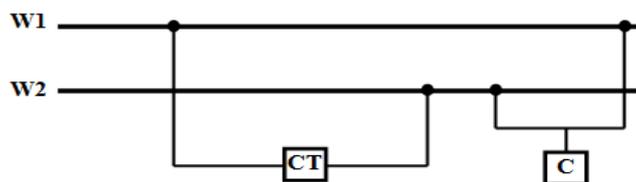
Fig.13. Simple cross - sectioned busbars type 1
W1; W2 - simple unconnected busbars systems;
CT - transverse coupling,
C - power cell.

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It is used for all voltage levels, by closing the transverse coupling the power cells have double power supply, thus increasing the reliability of the power substation.

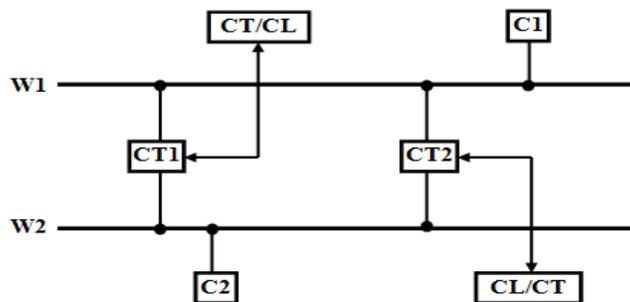### 2.4.4. Not sectioned simple cross-sectioned busbars type 2:

Fig.14. Sectioned longitudinally and bypass busbars
W1, W2 - non-dissected busbars system;
CT1, CT2 - transverse couplings;
CT / CL - transformer cell and / or line cell;
CL / CT - cell line and / or transformer;
C1, C2 - other power cells connected to busbars.

It is mainly used at VHV and UHV power substations.

By closing the transverse torques, the electric cells have a double supply, thus increasing the reliability of the power substation.

An arrival at the power substation can be from a transformer, thus charging on the respective bar, and a departure can be in the OHL.

Very high elasticity in operation.

2.4.5. The busbars system, a simple one not sectioned and a simple one sectioned longitudinally:
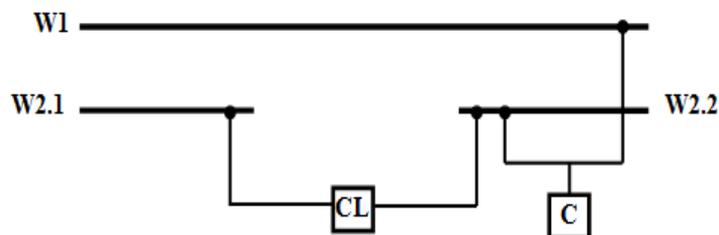
Fig.15. System, a simple one not sectioned and a simple one sectioned longitudinally busbars
W1 - simple non-dissected busbars system;
W2.1 .; W2.2. - simple busbar system cut longitudinally;
CL - longitudinal coupling;
C - power cell.

It is used for all voltage levels, very low elasticity in operation, very low reliability of

the station.

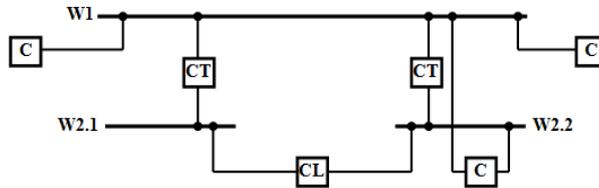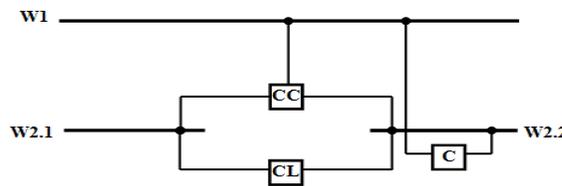### 2.4.6. Longitudinally sectioned busbars system with type 1 bypass busbars:

Fig.16. Longitudinally sectioned busbars system with type 1 bypass busbars

W1 - busbars with bypass; W2.1. - W2.2. - double sectioned busbars system;
C - power cells

It is mainly used at HV, VHV and UVH power substations.

In order to increase the continuity in the consumers' supply, the schemes with simple longitudinal sectioned busbars system can be associated with the bypass.

For a high elasticity in the operation of such schemes, corresponding to each busbars node, individual couplings can be provided, one longitudinal and two bypass (transverse).

2.4.7. Longitudinally sectioned busbars system with type 2 bypass busbars:

Fig.17. Longitudinally sectioned busbars system with type 2 bypass busbars
W1 - busbars with bypass; W2.1. - W2.2. - double sectioned busbars system;
CC - combined torque (long-transverse);
C - power cell.

It is mainly used at HV, VHV and UHV power substations.

The main disadvantage of using these multi-function couplings is that in case of overhaul or failure of the coupling switching element, all possibilities of coupling the various nodes between them are lost. In the event of a rejection of the single coupling element, the entire station is disconnected.

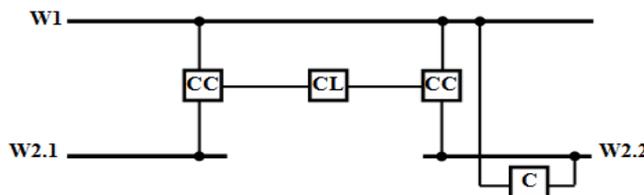### 2.4.8. Longitudinally sectioned busbars system with type 3 bypass busbars:

Fig.18. Longitudinally sectioned busbars system with type 3 bypass busbars
W1 - busbars with bypass; W2.1. - W2.2. - double sectioned busbars system;
CC - combined couplings (long-transverse);
CL - longitudinal coupling;

C - power cell.

It is mainly used at HV, VHV and UHV power substations.

By a convenient selection of bar separators, with the help of such a coupling three couplings can be made in a row (2 long-transverse and one longitudinal).

The main disadvantage of using these multi-function couplings is that in case of overhaul or failure of the coupling switching element, all possibilities of coupling the various nodes between them are lost.

In the event of a rejection of the single coupling element, the entire power substation is disconnected.

2.4.9. Not sectioned double busbars system - U-linking of busbars:
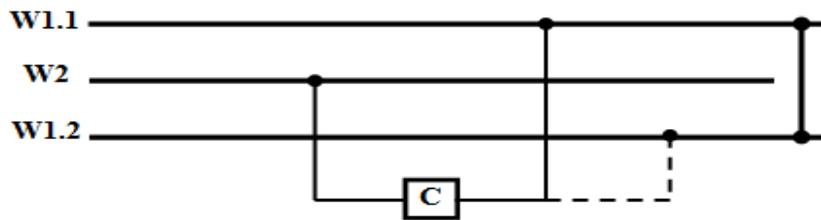

Fig.19. Double unconnected busbars system – U-linking of bars
W1.1 - W1.2 - double system of unsected busbars - U-linking of busbars;
W2. – Simple busbars not dissected;
C - power cell.

It is mainly used at VHV and UHV power substations.

By U-linking of busbars W1.1. and W1.2. it is transformed with the help of busbars W2 into a double supply for the respective power cell, few materials, almost zero reduced maintenance due to the lack of torques.

2.4.10. Not sectioned double busbars system - U-linking of busbars with transfer
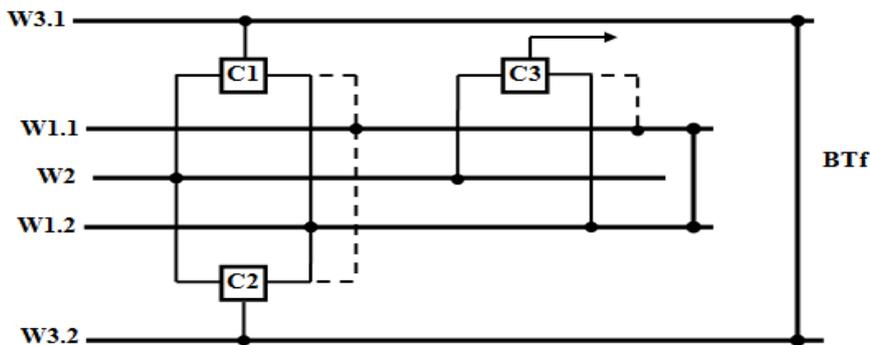

Fig.20. Double system of unconnected busbars - U-linking of the busbars with transfer busbars
W1.1. - W1.2. - double system of unsected busbars - U-linking of busbars;
W2. - Simple busbars not dissected;

W3.1. - W3.2. - busbars transfer;
C1, C2 - important power cells;
C3 - less important power cell;
BTf - busbars transfer

It is mainly used at VHV and UHV power substations.

By U-linking of busbars W1.1. and W1.2. it is transformed with the help of busbars W2 into a double food for the respective consumers.

The transfer bar acts as a double feed for various more important consumers. More materials by inserting the transfer bar, more extensive maintenance.

3. CONCLUSIONS

Primary circuits are the backbone of power transmission substations. They are responsible for transmitting electrical energy from generation stations to distribution networks while ensuring reliability, safety, and stability of the power system. The primary circuit components include power transformers, busbars, circuit breakers, isolators, instrument transformers, and protection relays, each serving a critical role in energy flow and control.

The significance of primary circuits can be analyzed from multiple perspectives:

1. Reliability and Continuity of Supply: Power substations are nodes in the transmission network where energy is routed and transformed. Proper configuration of primary circuits ensures minimal interruption during load fluctuations or faults, making them essential for uninterrupted power supply;

2. System Protection: Primary circuits are equipped with circuit breakers and protective relays that detect abnormal conditions such as short circuits, overcurrent, and overvoltage. Rapid isolation of faulty sections protects equipment from damage and prevents cascading failures in the grid;

3. Voltage Transformation and Regulation: Transformers in primary circuits step up or step down voltage levels according to transmission or distribution requirements. This is critical for minimizing transmission losses and maintaining power quality across long distances;

4. Critical Infrastructure Consideration: Transmission substations form part of a nation's critical energy infrastructure. Disruption in primary circuits can compromise energy security, impact industrial operations, and affect civilian life. Therefore, understanding and maintaining these circuits is central to resilient energy infrastructure planning;

5. Operational Flexibility: Primary circuit design allows network reconfiguration in real-time for maintenance or emergency conditions, which ensures optimal energy distribution without compromising system stability.

The strategy for designing and operating primary circuits in power transmission substations involves careful planning to optimize efficiency, reliability, and resilience.

Key strategic considerations include:

1. Circuit Configuration

Substation primary circuits can be configured in several ways, including single bus, double bus, ring bus, and breaker-and-a-half configurations. Each configuration offers specific advantages:

- *Single Bus:* Simplest design; low cost but minimal reliability. Faults on the bus can disrupt the entire system;
- *Double Bus:* Increases operational flexibility and reliability; maintenance on one bus does not interrupt supply;
- *Ring Bus:* Offers a compromise between cost and reliability; facilitates sectionalization to isolate faults;
- *Breaker-and-a-Half:* Provides high reliability and flexibility for critical substations; common in large transmission networks.

2. Component Selection and Protection

Primary circuits are designed with components selected for voltage rating, current rating, fault capacity, and operational lifetime. Protection schemes are tailored using current and voltage transformers for measurement and isolation. Strategies include:

- Selective Protection: Ensures only the faulty section is disconnected;
- Redundancy: Multiple circuit paths or breakers enhance reliability;
- Automation: Integration of SCADA systems allows remote monitoring and fault response, improving operational efficiency;

3. Maintenance and Monitoring Strategy;

- Preventive Maintenance: Regular inspection of breakers, isolators, and transformers to prevent failures;
- Condition-Based Monitoring: Use of sensors to track parameters like oil quality in transformers, temperature, and vibration to anticipate failures;
- System Upgrades: Incorporating digital relays and smart grid technologies enhances monitoring and responsiveness.

4. Critical Infrastructure Considerations

- Cybersecurity and Physical Security: Substations are vulnerable to cyberattacks and physical sabotage. Strategic planning involves robust firewalls, intrusion detection, and perimeter security;
- Resilience Planning: Backup power sources, redundancy, and emergency response plans ensure minimal disruption to the grid during unforeseen events.

The configuration and functionality of primary circuits in power transmission substations play a pivotal role in ensuring the stability, reliability, and efficiency of modern electrical grids. Primary circuits – including busbars, transformers, circuit breakers, disconnectors, and current and voltage transformers – form the backbone of substation operations. Their proper design and integration allow for the controlled flow of electrical energy from generation sources to distribution networks, while simultaneously providing protection against faults, overloads, and abnormal operating conditions.

Through careful configuration, primary circuits enable flexibility in operation, allowing maintenance without disrupting power supply and supporting load management in dynamic grid conditions. The selection of equipment, connection

schemes, and protection coordination directly influences system resilience, minimizing downtime and reducing the risk of cascading failures that could affect large geographical areas. Moreover, the functionality of these circuits is crucial in the context of critical energy infrastructure, where reliability is not only an economic necessity but also a matter of national security. Substations must therefore adhere to stringent operational standards, incorporating redundancy, rapid fault isolation, and advanced monitoring to detect and respond to disturbances in real time. Advances in automation and digital control systems have further enhanced the capabilities of primary circuits, enabling predictive maintenance, fault diagnostics, and remote operation, thereby strengthening the resilience of transmission networks. However, the increasing complexity of power systems – driven by renewable integration, decentralized generation, and smart grid technologies – requires continuous evaluation and optimization of substation configurations to maintain optimal performance.

In summary, the configuration and functionality of primary circuits in power transmission substations are central to the effective delivery of electrical energy and the protection of critical infrastructure. Their design, operation, and continuous modernization ensure not only reliable power supply but also the resilience and security of the energy system, making them indispensable components in the management of contemporary and future electrical networks.

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TRANSITIONING FROM SERIAL TO PARALLEL RISK ASSESSMENT IN THE INCIDENT RESPONSE LIFECYCLE OF SCADA-CONTROLLED HIGH-VOLTAGE TRANSMISSION SYSTEMS

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Abstract: The analysis of an overhead transmission line with directional relay and SCADA coordination demonstrates that serial assessment highlights system sensitivity to single-point failures, while parallel assessment shows the substantial reliability benefits of redundant protection paths. Environmental and equipment-related risks, such as storms/lightning, line/cable failures, and transformer/substation failures, are the primary contributors to global risk and should be prioritized for mitigation. Although regulatory and cyber-security risks have lower likelihood, their high-consequence potential requires continued monitoring. Fault tree methodology combined with likelihood-consequence metrics provides a rigorous framework for evaluating and managing system reliability.

1. ENERGETIC RISKS INTERDEPENDENCIES STANDARDS MAPPING

Electrical Protection Relays Safety Management involves ensuring that protection relays function correctly to safeguard electrical systems, equipment, and personnel. This includes the design, installation, maintenance, testing, and operation of relays. Effective safety management minimizes the risk of electrical faults, equipment damage, and injuries.

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Key Aspects of Safety Management in Electrical Protection Relays [1] are:

1. Design and Installation:

Choose appropriate relay types (e.g., overcurrent, differential, distance, and earth fault relays) based on system requirements. Ensure correct relay settings to match the system's fault current levels and time coordination. Follow electrical safety standards such as IEC 60255, IEEE C37 series, and local regulations.

2. Safety Procedures and Precautions: De-energize equipment before relay installation or maintenance. Use proper personal protective equipment (PPE) like insulated gloves and arc-flash suits. Implement lockout/tagout (LOTO) procedures to prevent accidental energization. Ensure only qualified personnel handle relay systems.

3. Testing and Commissioning:

Conduct thorough commissioning tests, including primary injection, secondary injection, and functional tests. Verify relay trip settings, time delays, and coordination with upstream and downstream devices. Document test results and compare them with design specifications.

4. Maintenance and Inspection:

Perform periodic maintenance as per manufacturer recommendations and industry standards. Inspect relay contacts, coils, and wiring for wear or damage. Regularly calibrate relays to ensure accurate operation. Use advanced diagnostic tools like relay test kits and simulation software.

5. Monitoring and Performance Analysis:

Continuously monitor relay performance through SCADA systems or other remote monitoring platforms. Analyze relay operation logs and fault records to identify patterns and potential issues. Investigate false trips and non-operation incidents to improve reliability.

6. Documentation and Compliance:

Maintain detailed records of relay settings, test results, maintenance activities, and fault events. Ensure compliance with safety regulations, electrical codes, and industry best practices. Update documentation when system configurations or relay settings change.

7. Training and Competency:

Train personnel on relay operation, testing, and troubleshooting. Ensure competency in using test equipment, interpreting relay settings, and understanding fault waveforms. Conduct regular refresher training to keep up with technological advancements. The conceptual representation with interdependencies is shown in figure 1, adapted from [1], [2]:

IEC 60255 and IEEE C37 standards are important specifically for safety management of electrical protection relays. Protection relays are safety-critical devices. Any failure—false tripping, failure to trip, or unsafe handling—can result in equipment damage, widespread outages, or serious injury. IEC 60255 and IEEE C37 standards provide a globally accepted framework to control these risks across the entire relay lifecycle. For designing these interdependencies next, we show the map of the main involved standards [2], [3].

| Block	Standard Annotation
Design & Installation	IEC 60255-1, IEC 60255-26, IEEE C37.90
Safety Procedures & Precautions	IEEE C37.20.2, IEEE 1584
Testing & Commissioning	IEC 60255-121, IEEE C37.233
Maintenance & Inspection	IEEE C37.10, IEC 60255-1
Monitoring & Performance	IEC 60255-24
Documentation & Compliance	IEC 60255 (series), IEEE C37 (series)
Training & Competency	IEC 60255-1 (competency requirement)
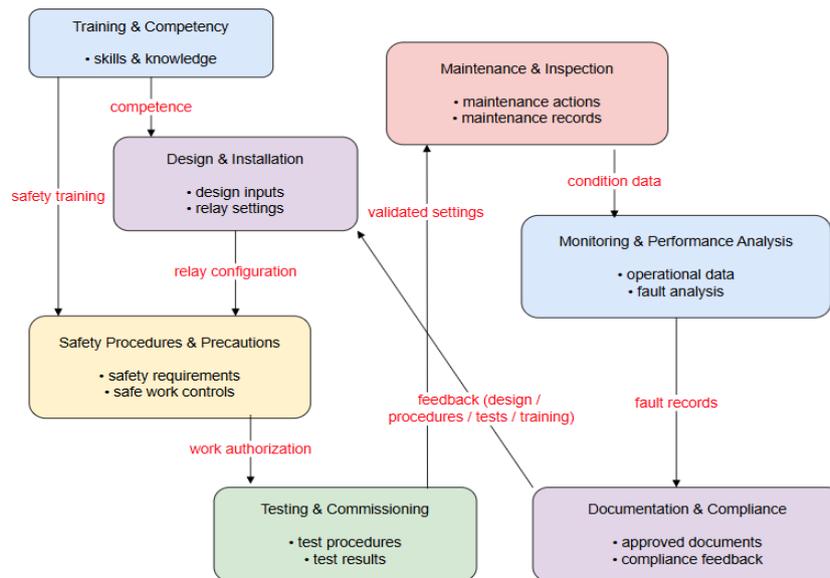
Fig.1. UML Block Diagram using SysML-style blocks, which is the correct UML family for engineering systems like protection relays of most common interdependencies

2. SERIAL RISK ASSESSMENT AND PARALLEL RISK ASSESSMENT APPROCHES TO AN INDUSTRIAL PROCESS

2.1. Serial Risk Assessment

In a serial risk assessment, risks are evaluated one after the other, in a sequential manner [4]. This is a more traditional approach, where each risk is identified, analyzed, and mitigated step-by-step.

Key Characteristics:

1. Step-by-Step Process: Risks are assessed one at a time, and solutions are implemented sequentially.

2. Time-Consuming: Since each risk must be evaluated individually, the process can take a longer time to complete, especially if there are many risks to consider.

3. Risk Interdependence: This method may overlook how risks interact or overlap with each other, as each is considered in isolation.

4. Limited Resources: This approach can be resource-intensive as it often requires dedicated time and attention for each risk, potentially causing delays in decision-making.

Example: In a large infrastructure project, the risks of design errors, budget overruns, and labor shortages might be assessed one at a time, and solutions for each would be put in place before moving to the next risk.

2.2. Parallel Risk Assessment

In parallel risk assessment, risks are evaluated simultaneously, with multiple risks being assessed at the same time [4]. This approach is more dynamic and is often used when multiple teams or resources are available to handle different aspects of risk assessment at once.

Key Characteristics:

1. Simultaneous Evaluation: Multiple risks are identified, analyzed, and addressed at the same time.

2. Faster Process: Because several risks are being tackled concurrently, the assessment process can be faster and more efficient.

3. Holistic View: The approach allows for a better understanding of how risks might interact with each other, providing a more integrated solution.

4. Resource-Intensive: While it can speed up the process, this method often requires more resources (e.g., personnel, tools, or teams) to assess risks in parallel.

Example: In the same infrastructure project, different teams might be assessing and addressing risks related to design, budget, and labor simultaneously, ensuring faster identification of interrelated risks and quicker decision-making.

To simply, next table indicates key differences:

Aspect	Serial Risk Assessment	Parallel Risk Assessment
Risk Evaluation	One risk at a time	Multiple risks evaluated at once
Speed	Slower (step-by-step)	Faster (simultaneous analysis)
Resource Requirements	Less resource-intensive per risk	More resource-intensive (needs multiple teams or tools)
Interdependencies	May overlook interrelationships between risks	Allows for better understanding of risk interdependencies
Complexity	Simpler process, more manageable	Can be complex and require careful coordination

3. THE MODEL FOR RISK ASSESSMENT APPROACHES IN PROTECTED OVERHEAD TRANSMISSION LINES

3.1. Serial Risk Assessment in High Voltage Transmission Lines

In a serial risk assessment for high voltage transmission lines, the focus would be on evaluating each risk one at a time, typically with a step-by-step approach. The core idea is: in serial risk assessment treats the system as a chain of dependent elements where failure of any one component in the sequence can cause loss of protection, incorrect

operation, or inability to clear faults. Simplified: everything must work, in order, for the protection function to succeed.

The protection and control function can be modeled as a series path, for example [5]:

- Overhead transmission line develops a fault
- CTs / VTs correctly sense current and voltage
- Directional protection relay correctly:
  - Polarizes direction
  - Detects fault
  - Issues a trip command
- SCADA communication path is available (if required for blocking, permissive, or supervision)
- Breaker receives trip signal and operates
- If any one of these fails, the protection objective fails.

3.2. Parallel Risk Assessment in High Voltage Transmission Lines

A parallel risk assessment would evaluate several risks simultaneously, taking advantage of available resources to handle multiple risk factors at once. The process might involve multiple teams or departments handling different types of risks concurrently, allowing for a more holistic approach to managing the infrastructure. The core idea is: in parallel risk assessment assumes that multiple independent paths can successfully perform the protection or control function, and only simultaneous failures lead to unacceptable outcomes. Simplified: the system survives as long as at least one path works.

This approach is relevant if your system includes redundant or diverse elements, such as [5]:

- Local relay operation independent of SCADA
- Backup protection zones (e.g., distance + directional OC)
- Redundant communication channels
- Local breaker failure protection
- Independent control paths (local vs remote trip)

Example parallel structure:

- Path A: Local directional relay → breaker trip (no SCADA dependency)
- Path B: SCADA-assisted scheme (permissive/blocking)

The key contrast between two approaches is shown in next table:

| Aspect	Serial Risk Assessment	Parallel Risk Assessment
View of system	Single dependency chain	Multiple independent paths
Failure logic	Any failure causes loss	All paths must fail
Risk trend	Increases with complexity	Decreases with redundancy
Focus	Weakest link	Common-mode failures
Best for	Identifying single points of failure	Evaluating redundancy benefits
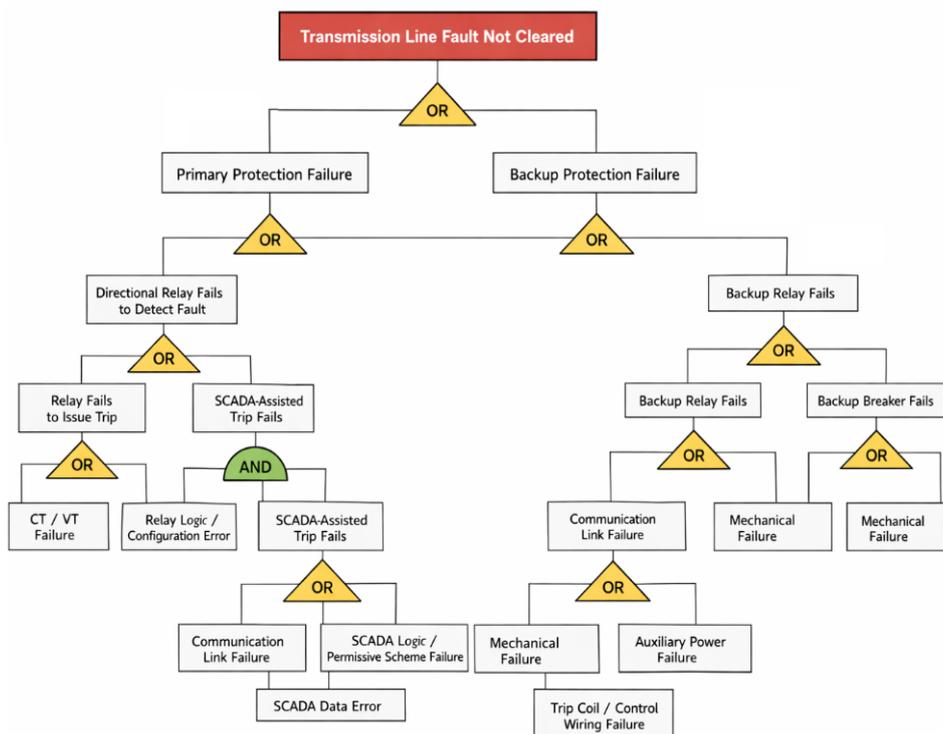
Fig.2. The visual fault tree diagram for this configuration with proper OR/AND gates, showing the hierarchy clearly for the proposed configuration

Most real-world protection systems use both approaches together:

Serial assessment to identify:

- SCADA single-point dependencies
- Relay setting or logic vulnerabilities

Parallel assessment to verify:

- Local relay action remains effective without SCADA
- Backup protection truly operates independently

The next picture shows the fault three for define configuration through both approaches.

The first fault tree effectively captures the serial and parallel dynamics of the protection system, highlights critical single points of failure, and lays a foundation for integrating environmental, cyber, and regulatory risks. The explanation is:

Top Event:

- "Transmission Line Fault Not Cleared" clearly defines the ultimate undesired outcome. It sets the focus on system protection reliability.

Primary vs Backup Paths:

- The tree splits into Primary Protection Failure and Backup Protection Failure, representing redundant protection paths. This naturally aligns with parallel risk assessment, highlighting system resilience.

Serial Dependencies:

- Within the primary path, failure propagates through CT/VT → Relay → SCADA → Breaker. This captures serial risk, where any single failure can prevent fault clearing.

AND/OR Gates:

- OR gates dominate the tree, representing failures where any single event triggers parent failure.
- AND gates are used in the SCADA + relay + breaker combination, modeling situations where all components must fail to cause the top event — this was the improvement to reflect serial-path dependencies more realistically.

Coverage:

- Major equipment failures, communication/SCADA dependency, and breaker operation are included.
- The tree is modular, so additional risks (environmental, cyber, regulatory) can be integrated easily.

Utility:

- It provides a clear hierarchical visualization of risk contributors.
- Supports both quantitative analysis (probability calculations) and risk mitigation planning.

4. ADDING RISKS TO THE PROPOSED CONFIGURATION AND CALCULATING THE RISKS

4.1. Categorized Risk Identification

They are summarized in next table.

Category	Identified Risk	Notes / Relevance
Equipment / System	Transformers, cables, substations failure	Could lead to primary or backup protection failure, breaker trips, or relay malfunction. Connects directly to **serial path risks** in your fault tree.
Environmental	Storms, lightning, heavy rain	May damage transmission lines, affect CT/VT inputs, or SCADA communications.
	Flooding	Impacts lines near water, substations, or communication infrastructure. May trigger backup protection if primary fails.
	Wildfires	Can physically damage lines or towers, cause relay or SCADA malfunctions.
Security / Cyber	Terrorism, sabotage	Risk of physical attack on lines, substations, or SCADA links. Can cause simultaneous failure in multiple paths (parallel risk scenario).

	Cyber-attacks	May disrupt SCADA coordination, trip logic, or communications. Directly impacts SCADA-assisted paths in the fault tree.
Regulatory / Compliance	Non-compliance with environmental or safety standards	May indirectly affect system reliability, increase liability, or force operational restrictions.

4.2. Mapping to Fault Tree / Risk Assessment

Serial risk perspective:

- Equipment failures (CT/VT, relays, breakers) are single-point failures that propagate along the primary protection path.
- Environmental risks (storms, floods, lightning) can disable multiple serial components, e.g., a relay plus SCADA link failure.

Parallel risk perspective:

- Security threats, wildfires, or flooding can cause simultaneous failure of redundant paths, affecting both primary and backup protection.
- SCADA dependency is a shared node; cyber-attack or communication failure can compromise multiple paths at once.

4.3. Suggested Risk Register Table

Risk	Category	Fault Tree Impact	Likelihood	Conseq	Risk Level
Transformer/Substation Failure	Equipment	Primary / Backup relay/trip failure	Medium	High	High
Cable / Line Damage	Equipment / Environmental	CT/VT loss, breaker trips	Medium	High	High
Storms / Lightning	Environmental	Relay failure, communication loss	Medium	Medium	Medium
Flooding	Environmental	Communication, line, or substation damage	Low	High	Medium-High
Wildfires	Environmental	Line or relay failure	Low	High	Medium-High
Terrorism / Sabotage	Security	Simultaneous path failures	Low	Very High	High
Cyber-attack	Security	SCADA failure, miscoordination	Low	High	Medium-High
Regulatory Non-compliance	Regulatory	Operational restrictions	Low	Medium	Medium

Serial risk assessment evaluates each path individually. Parallel risk assessment evaluates redundancy and simultaneous failures. calculate global/system risk for your

transmission line + directional relay + SCADA configuration, we need to handle Serial vs Parallel approaches differently.

4.4. Serial Risk Assessment Overall Failure Probability

In a serial system, any single failure along the protection path causes system failure. If we assume:
- o   Each component i has a failure probability P_i
- o   Failures are independent

Then the overall failure probability along a serial path is:

$$P_{serial\ system} = 1 - \prod_i (1 - P_i)$$

If we consider the approximate failure probabilities like in next table we are able to compute serial risk (all required elements along primary protection).

Component / Risk	Serial Failure Probability Pi
CT/VT failure	0.002
Relay hardware / logic error	0.003
Breaker failure	0.001
SCADA-assisted trip failure	0.002
Environmental events (storm, flood, wildfire)	0.004
Cyber-attack / sabotage	0.001

The result is $P_{serial\ system}$=1.2%. It means that ~1.3% chance per year that the line fault is not cleared due to a single failure along the primary path.

4.5. Parallel Risk Assessment Overall Failure Probability

In a serial system, backup paths exist, so the system fails only if all independent paths fail simultaneously. With similar calculations we have:

Primary path failure probability: $P1 = 0.01294$

Backup path failure probability: P2=0.008 (assume backup relay + breaker + independent SCADA path)

Then overall parallel failure probability: $P_{parallel\ system} = P_1 * P_2$ =0.01% (With redundancy, the system failure drops dramatically — about 1 in 10,000 per year)

The immediate step is related to define exact risks categories. It is necessary to:
1. Assign likelihoods (failure probabilities per year)
2. Assign consequence scores (impact if risk occurs, 1–5 scale)
3. Calculate risk = likelihood × consequence
4. Calculate global/system risk for serial and parallel approaches

Likelihoods are annual probabilities; consequences are scored 1–5 (5 = highest impact). After calculations, the serial global risk score: 0.084 (~8.4% "risk units" per year), and the parallel risk score is: 0.00148 (0.15%).

5. CONCLUSIONS

Serial assessment highlights weak points along the protection chain.

Parallel assessment shows benefits of redundancy (backup protection, independent SCADA, multiple communication paths).

Environmental and security risks significantly affect serial risk, but parallel redundancy mitigates them.

The reliability analysis of an overhead transmission line protected by a directional relay and SCADA coordination was conducted using fault tree methodology to systematically identify and quantify potential failure modes. Serial risk assessment revealed that the system is highly sensitive to single-point failures, with any fault along the primary protection path potentially preventing successful clearing of line faults, illustrating the cumulative effect of component-level risks. In contrast, parallel risk assessment demonstrated the significant benefits of redundancy: independent operation of primary and backup protection paths reduced the overall system risk by approximately fifty-fold, highlighting the critical role of redundant architectures in enhancing power system resilience.

Quantitative evaluation based on likelihood-consequence metrics identified environmental and equipment-related hazards as the dominant contributors to global risk, specifically storms/lightning (risk score = 0.020), line/cable failures (0.016), and transformer/substation failures (0.015), which should be prioritized for mitigation. Although regulatory non-compliance and cyber-security threats presented lower probabilities and correspondingly smaller numerical risk contributions, their potential for high-consequence outcomes underscores the necessity of continued monitoring and targeted mitigation to maintain system robustness. This integrated approach, combining fault tree analysis with risk scoring, provides a rigorous framework for assessing and managing complex protection systems in overhead transmission networks.

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MEASURES OF OPERATION ADOPTED FOR REDUCING ENERGY LOSSES IN ELECTRICAL NETWORKS

ANDREI CRISTIAN RADA[1]

Abstract: Industry and services are the largest consumers of active electrical energy. Due to the wide variety of equipment and their generally low and highly variable loading levels, the overall energy efficiencies are also relatively low compared to other economic sectors. These reduced efficiencies are the result of the design, operational, and maintenance characteristics of all electrical equipment (motors, transformers, lines, switching devices, etc.). Reducing energy losses in electrical networks significantly increases the efficiency of specific activities. Both operational practice and specialized technical literature indicate that various methods can be applied to reduce energy losses. The present paper aims to highlight the measures adopted to decrease electrical energy losses in power networks.

Key words: energy losses, transformers, no-load operation, automatic control, economic operating regime

1. INTRODUCTION

Reducing energy losses in electrical networks is one of the main concerns of distribution and transmission operators, as it directly influences the efficiency of the power system. In the context of continuously increasing demand and increasingly strict sustainability requirements, optimizing the operation of electrical infrastructure becomes essential. Technical and commercial losses affect both economic performance and the quality of the electricity delivered to end users. Implementing modern operational measures, based on advanced monitoring and smart technologies, enables an effective and sustainable reduction of these losses. By adopting such solutions, electrical networks can improve their long-term reliability, stability, and competitiveness [1], [4].

These measures fall into the category of actions that do not require additional costs but rely on proper and professional operation of the installations to minimize electrical energy losses.

The main operational measures that lead to loss reduction are:
- limiting the no-load operating time for all electrical energy consumers;

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- increasing the utilization time of the maximum load or flattening the load curve;

- correctly selecting the tap changer positions for voltage regulation in power transformers;

- optimizing the operating regime of electrical lines and power transformers.

2. REDUCING THE IDLE OPERATING TIME OF ELECTRICAL CONSUMERS

The issue of limiting no-load operating time is not dependent on the nature of the work process, yet it is one of the most important and effective methods for saving electrical energy.

The no-load operating regime is defined as the condition in which electrical machines or installations remain energized during technological pauses, so that the equipment operates without producing useful mechanical work, while consuming a certain amount of active and reactive electrical energy. These losses may vary between 15% and 45%, depending on the type of load [4], [9].

Limiting the no-load operating regime for a specific type of consumer must necessarily be correlated with the operating mode of the motor that drives that consumer. In practice, three main operating regimes can be identified:

- long-duration operation with constant load;
- intermittent load operation;
- short-duration load operation.

2.1. Limiting no-load operation for installations with long-duration operating regimes and constant load over time

These consumers operate under a uniform working regime, with the motors developing an approximately constant torque. The automatic control scheme for disconnecting installations during no-load operation is shown in Fig. 1 and is based on the observation that the power absorbed at no-load is significantly lower than the power absorbed during normal operation. The element serving as the transducer (which collects the primary information) is an undercurrent relay that issues a time-delayed command for disconnecting the installation from the network.

The scheme includes a current relay RC, adjusted to operate at approximately $1{,}1 \cdot I_0$ (1,1 times the no-load current). During normal operation, since the current flowing through relay RC is much higher than the set value, its normally-closed contact remains open, preventing the time relay from being energized. During the starting period, when the current is considerably higher, contact RC_1 will also remain open.

If the absorbed current drops below the set threshold, contact RC_1 returns to its normal position (closing), thereby energizing the coil of the time relay, which begins its timing cycle. If the current does not increase during the preset delay, the time relay RT_p will de-energize the coil of contactor C by opening contact RT_{p1}, which in turn interrupts the power supply to the electric motor. The time relay can be adjusted within

a range of 1 to 10 minutes. Restarting the motor can be done only through a deliberate command, by pressing the start button *P* [5], [10].
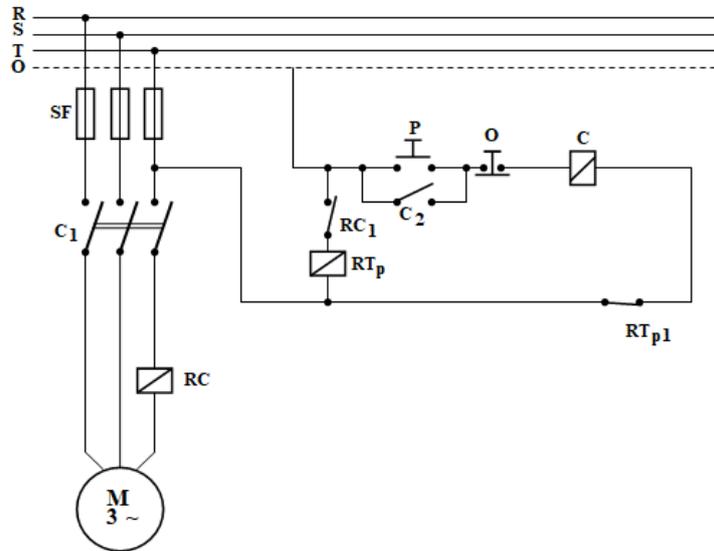

Fig.1. Automatic no-load disconnection scheme for motors with constant load over time

The no-load limiting control is also widely used for single-phase welding transformers, since in addition to generating no-load losses, they also cause unbalance in the three-phase network. The automatic control scheme for limiting no-load operation in welding transformers is shown in Fig. 2.
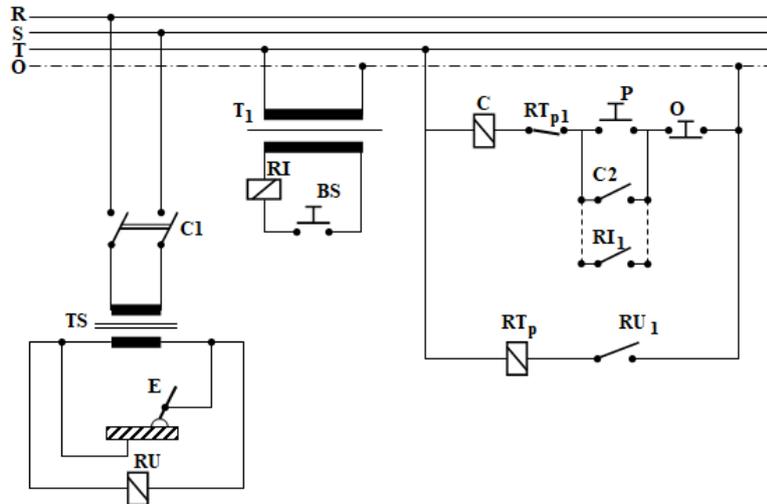
Fig.2. Network disconnection scheme for welding transformers during no-load operation

Single-phase welding transformers have a no-load voltage of 60 –75 V. This voltage is hazardous to personnel working in the area. The voltage relay *RU* (the

transducer) detects the voltage rise when the electric arc is interrupted for any reason. It closes contact RU_1, energizing the coil of the time relay, which begins its timing cycle (3 – 5 minutes). If the electric arc is not reestablished during this period, contact RT_{p1} opens, the contactor coil is de-energized, and contacts C_1 open, disconnecting the welding transformer *TS* from the network [1], [4], [5], 11].

To avoid the need for the operator to move between the work station and the location of the transformer when reconnecting it to the network, an additional button *BS* is provided. Pressing this button energizes an intermediate relay *RI* with a low voltage of 12 V or 24 V. Through its normally open contact RI_1, the contactor *C* can then be remotely engaged. This is one of the very few exceptions to occupational safety regulations that allow the simultaneous existence of two start buttons located in different places. This exception is permitted because only one person operates at the welding points, performing both the connection and disconnection commands of the welding transformer [13].

In the case of long-duration operating regimes with an approximately constant load over time, a clear distinction can be made between the load current and the no-load current. As a consequence, the presented schemes operate correctly under no-load conditions.

2.2. Limiting no-load operation for installations with intermittent or short-duration operating regimes

In these cases, the power absorbed during normal operation does not differ significantly from the no-load power, and the load–no-load operating periods follow each other rapidly or occur randomly in duration.

To establish the optimal scheme for limiting no-load operation in installations with such operating regimes, certain characteristic elements must be taken into account:

- the variation of power or current absorbed by the consumer during work transitions;
- frequent switching between normal load operation and technological pause (no-load), followed by repetition of the cycle;
- low energy consumption when operating under lightly loaded conditions, close to the no-load regime (as in machine tools in workshops, etc.) [6], [8], [12].

The operation of these schemes is based on utilizing the transient phenomenon that occurs between two stable operating regimes. The principal scheme is shown in Fig. 3.

The control scheme consists of a current relay *RC*, two-time relays RT_{p1} and RT_{p2}, and an intermediate relay *RI*.

The current relay detects fluctuations in the motor current during periods corresponding to different operating regimes. When the current drops, the current relay operates, and by closing contact RC_1, it energizes the coil of time relay RT_{p1}. After the preset delay, RT_{p1} energizes the intermediate relay *RI*, which latches itself through contact RI_2, deactivates time relay RT_{p1} via contact RI_1 (to allow the coil to cool), and through contact RI_3 energizes the coil of the second time relay RT_{p2}.
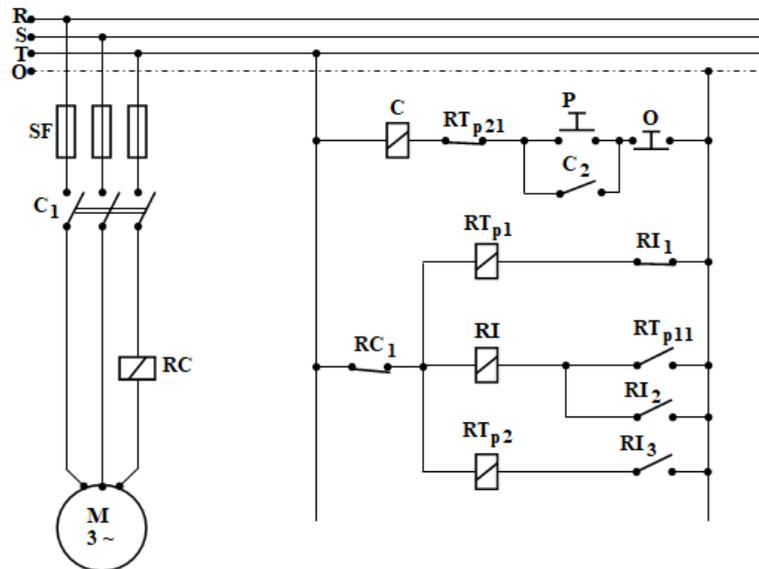
Fig.3. No-load disconnection scheme for consumers with intermittent or short-duration
operating regimes

If the motor current does not increase during the operation of RT_{p2}, the consumer will be disconnected from the network via contact RT_{p21}.

If the cycle repeats, the control scheme resets through the opening of contact RC_1, with the advantage that the relays are energized alternately, eliminating false disconnections.

These schemes become effective when the energy savings achieved by limiting no-load operation offset the investment costs associated with purchasing these devices. The same schemes can also be implemented using static switching elements, but the acquisition and maintenance costs must be carefully compared.

3. ENSURING EFFICIENT AND SAFE OPERATION OF ELECTRICAL NETWORK COMPONENTS

Case of Electrical Lines - when an electrical line carries current, energy losses occur due to the Joule–Lenz effect and the leakage reactance. Reducing losses in lines during operation is achieved through all well-known measures aimed at decreasing line loading (e.g., voltage adjustment, flattening the load curve, etc.).

Another way to reduce energy losses is by changing the operating regimes of lines that can function in parallel or in a double-line configuration.

The change in the operating regime of lines can be performed manually or automatically using specialized devices for automatic backup supply engagement (A.A.R.). Two such principle schemes are shown in Fig. 4.

In Fig. 4, unshaded rectangles represent circuit breakers in the closed position, while shaded rectangles represent the circuit breakers that are open and will be automatically controlled to modify the configuration in which the lines operate.
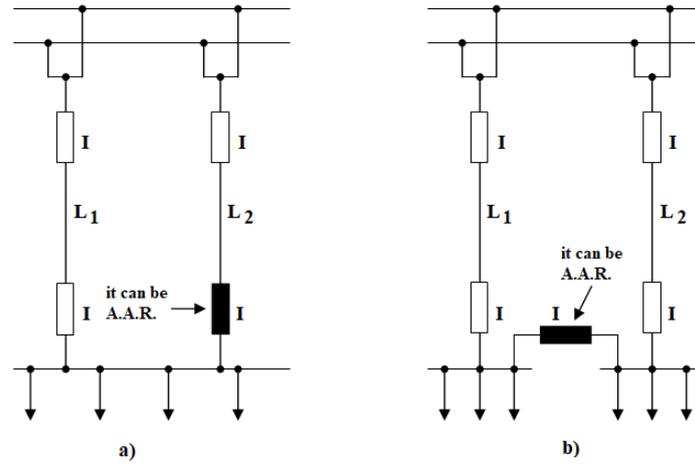
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Fig.4. Principle scheme with A.A.R. devices for changing the configuration of consumer supply lines

In Fig. 4 (a), line L_1 is in operation, while line L_2 is in reserve. In Fig. 4 (b), both lines are operating under partial load corresponding to the associated group of consumers. In both cases, the lines are rated for the full power required by the consumers, leaving the choice of the supply configuration that meets the required purpose or the economic criterion with minimum losses [2].

It should also be noted that these configurations provide a much higher level of safety, but they are not used for every consumer or electrical load.

Case of Power Transformers, the power transformers are essential components of electrical networks, as they enable the supply of large groups of consumers. During their operation, due to the Joule–Lenz effect and electromagnetic induction phenomena—fundamental principles of their operation—energy losses occur, both active and reactive [3]. These losses can be evaluated using the following relations:

$$\Delta P = \Delta P_{Fe} + \Delta P_{Cun}\left(\frac{S}{S_n}\right)^2 \tag{1}$$

$$\Delta Q = \Delta Q_{Fe} + \Delta Q_{Cun}\left(\frac{S}{S_n}\right)^2 \tag{2}$$

where
ΔP_{Fe} – active power losses occurring during no-load operation;
ΔQ_{Fe} – reactive power consumption of the transformer during no-load operation;
ΔP_{Cum} – active power losses during short-circuit operation;
ΔQ_{Cum} – reactive power losses during short-circuit operation;
S – the power at which the transformer is loaded;
S_n – the nominal apparent power.

If the energy equivalent of reactive power, denoted as ke [W/VAr or kW/kVAr], is included in the calculation, the power losses of the transformer can be determined using the following relations:

$$\Delta P_T = \Delta P_{Fe} + k_e \cdot \Delta Q_{Fe} + (\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun})\left(\frac{S}{S_n}\right)^2 \qquad (3)$$

If this expression is analyzed, it is found that its unit of measurement is [kW]. The expression consists of a constant part, denoted by m, which is equal to: $m = \Delta P_{Fe} + k_e \cdot \Delta Q_{Fe}$, and a variable part, dependent on the load factor, denoted by $n = (\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun})\left(\frac{1}{S_n^2}\right)$.

Using these two notations, the condensed calculation formula for the transformer power losses is given by the following relation:

$$\Delta P_T = m + n \cdot S^2 \qquad (4)$$

which is an equation of the form $y = a + bx^2$, that can be graphically represented as a parabolic curve, as shown in Fig. 5.
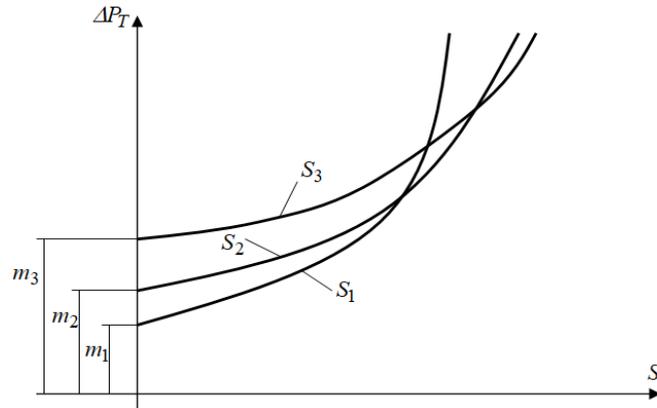

Fig.5. Graphical representation of transformer power losses as a function of the load demanded by consumers

By plotting the curves in Fig. 5, the values of m and n are determined, which vary for each transformer. Next, the power losses at different transformer loads are calculated, and these points are plotted on the coordinate system shown in Fig. 5. By connecting these points, the dependence $\Delta P_T = f(S^2)$ is obtained.

This mathematical model allows the determination of the economic operating range, either through analytical optimization methods or by using graphical methods.

In the case of multiple transformers at a substation or transformer station, these graphs are generated for each transformer individually, as well as for scenarios in which the transformers operate in parallel [3], [7].

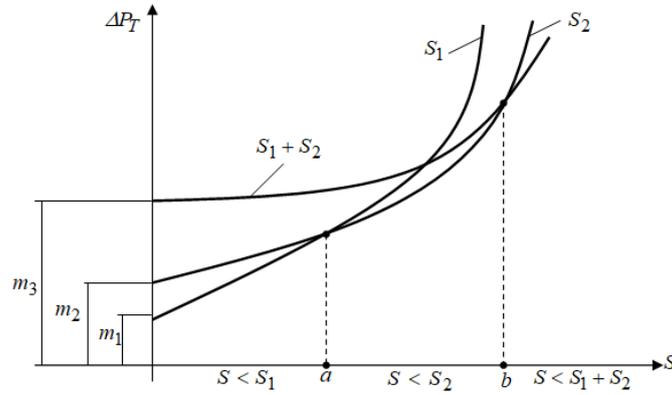Fig. 6 shows the power losses for two transformers operating either independently or in parallel.

Fig.6. Representation of power losses for transformers operating individually or in parallel

The economic operating regime is determined from the analysis of the graph, being associated with the minimum power losses. It can be observed that these minimum losses occur at certain transformer load levels, as follows:
- To the left of point a (corresponding to a certain actual power S), it is economical to operate only the transformer with apparent power S1, as it produces the lowest losses.
- Between points *a* and *b* on the power axis, it is economical to operate only the transformer with apparent power S_2.
- To the right of point *b*, it is economical to operate both transformers connected in parallel [3], [7].

Analytically, the economic operating regime is obtained by differentiating the power losses with respect to the apparent power S. The minimum power loss for a transformer is achieved when the losses in the magnetic circuit are equal to the losses in the windings ($\Delta P_{Fe} = \Delta P_{Cun}$).

The optimal apparent power of the transformer can be determined using the relation:

$$S_{opt} = S_n \sqrt{\frac{\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe}}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \qquad (5)$$

It is considered economical to switch to operation with multiple transformers in parallel by connecting an additional transformer to the network if the total losses are lower than those that occurred before connecting the transformer.

When a substation or transformer station has multiple transformers with the same nominal apparent power, the optimal power for the case in which all *N* transformers are connected in parallel is determined using the following relation:

$$S_{opt} = S_n \sqrt{\frac{N^2 (\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \qquad (6)$$

In the case of connecting another transformer with the same power (and identical technical characteristics), the calculation formula for the optimal apparent power is:

$$S_{opt} = S_n \sqrt{\frac{N(N+1)(\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \qquad (7)$$

In the case of disconnecting a transformer, the economic operating regime is achieved if the following condition is satisfied:

$$S_{opt} = S_n \sqrt{\frac{N(N-1)(\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \qquad (8)$$

The automatic connection and disconnection of transformers can be practically achieved by monitoring the current drawn by consumers and comparing it with a reference value, set by adjusting a current relay or a dedicated comparator circuit. The informational element used for this purpose can be a current transducer or a current relay. The control schemes for the automatic operation of transformers are, in principle, similar to those used for electrical lines [3], [7].

In general, it is considered that reducing energy losses through automatic switching of power transformers according to load is significant, given the long service life of these devices.

4. CONCLUSIONS

Efficient operation of transformers and electrical lines is crucial for minimizing energy losses, as these losses directly affect both the economic performance and the reliability of electrical networks. Proper monitoring and control of load conditions allow for significant energy savings.

Limiting no-load operation is one of the most effective and widely applicable methods for reducing unnecessary energy consumption in both motors and transformers. This method is particularly important for long-duration, intermittent, and short-duration operating regimes.

Automatic connection and disconnection schemes, based on current or voltage monitoring, enable the optimization of transformer operation, ensuring that transformers operate only when economically justified. These schemes also prevent false disconnections and improve operational safety.

The economic operating regime of transformers can be determined graphically or analytically, by identifying the load levels where power losses are minimal. Operating transformers individually or in parallel according to the load ensures optimal energy efficiency.

Configurable electrical lines and parallel transformer operation enhance both efficiency and reliability. Using automatic switching devices and proper load distribution reduces losses while maintaining a high level of safety for critical

consumers, though these solutions must be applied selectively based on the specific network and load requirements.

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