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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;

[1] *Ph.D., Lecturer Eng., University of Petroșani, radaandreicristian@gmail.com*

- 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].

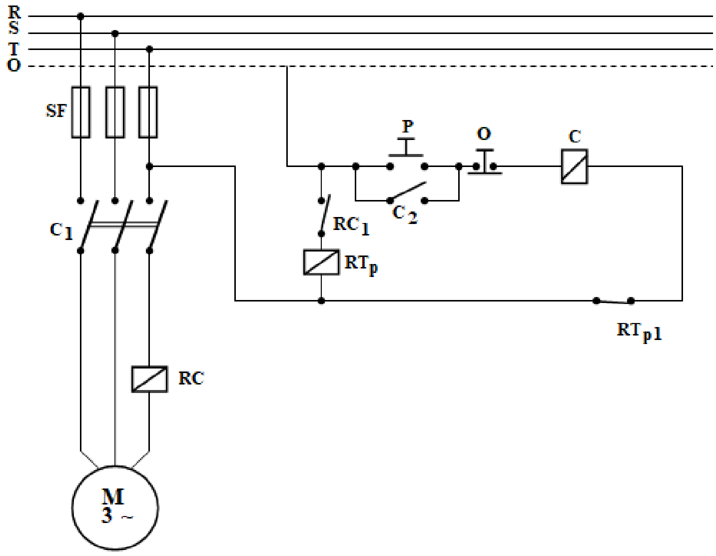

Fig.1. Automatic no-load disconnection scheme for motors with constant load over time

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.

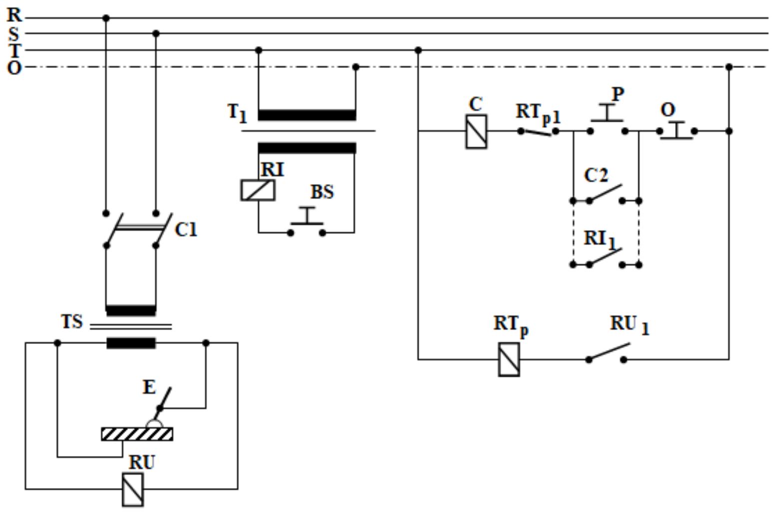

Fig.2. Network disconnection scheme for welding transformers during no-load operation

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}.

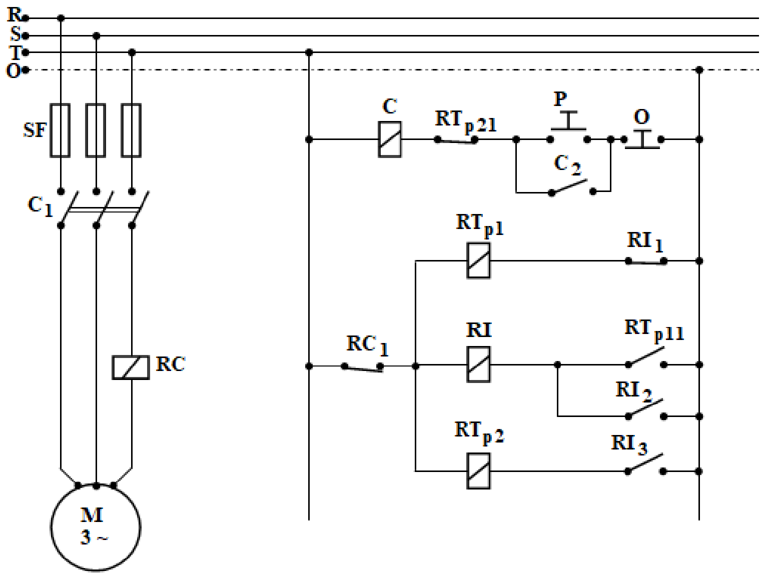

Fig.3. No-load disconnection scheme for consumers with intermittent or short-duration operating regimes

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.

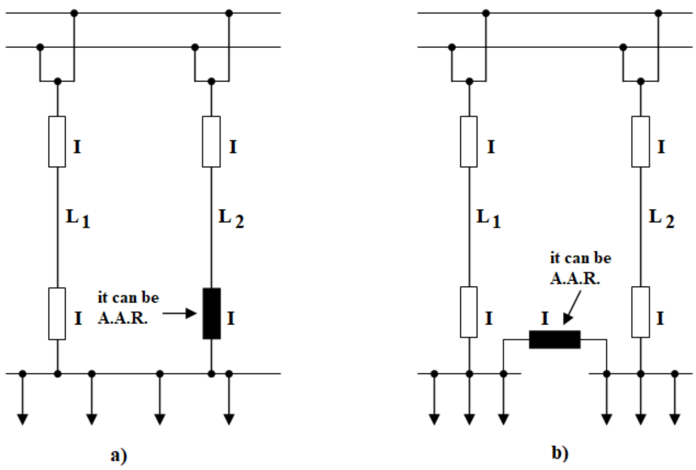

Fig.4. Principle scheme with A.A.R. devices for changing the configuration of consumer supply lines

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:

$$\Delta P = \Delta P_{Fe} + \Delta P_{Cun}\left(\frac{S}{S_n}\right)^2 \quad (1)$$

$$\Delta Q = \Delta Q_{Fe} + \Delta Q_{Cun}\left(\frac{S}{S_n}\right)^2 \quad (2)$$

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:

$$\Delta P_T = \Delta P_{Fe} + k_e \cdot \Delta Q_{Fe} + (\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun})\left(\frac{S}{S_n}\right)^2 \quad (3)$$

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:

$$\Delta P_T = m + n \cdot S^2 \quad (4)$$

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.

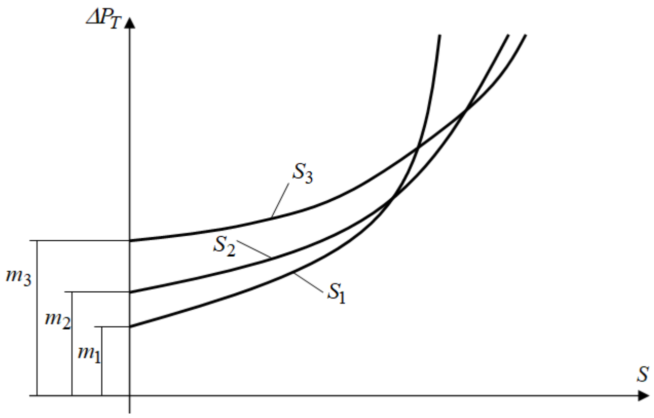

Fig.5. Graphical representation of transformer power losses as a function of the load demanded by consumers

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.

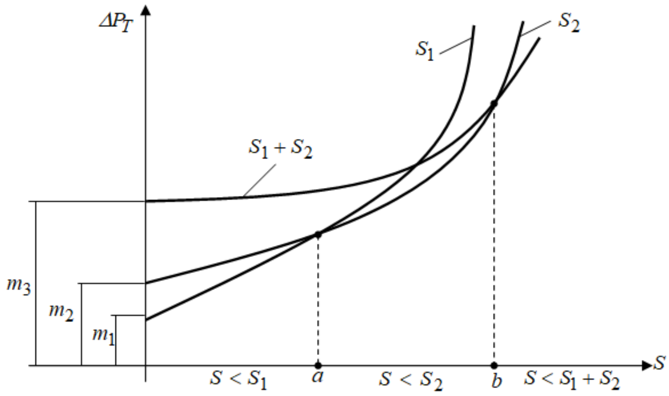

Fig.6. Representation of power losses for transformers operating individually or in parallel

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:

$$S_{opt} = S_n \sqrt{\frac{\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe}}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \tag{5}$$

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:

$$S_{opt} = S_n \sqrt{\frac{N^2 (\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \tag{6}$$

In the case of connecting another transformer with the same power (and identical technical characteristics), the calculation formula for the optimal apparent power is:

$$S_{opt} = S_n \sqrt{\frac{N(N+1)(\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \tag{7}$$

In the case of disconnecting a transformer, the economic operating regime is achieved if the following condition is satisfied:

$$S_{opt} = S_n \sqrt{\frac{N(N-1)(\Delta P_{Fe} + k_e \cdot \Delta Q_{Fe})}{\Delta P_{Cun} + k_e \cdot \Delta Q_{Cun}}} \tag{8}$$

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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