

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.*

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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 Insulated 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;*

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- *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 busbar system with 1 CB - circuit breaker

Name / Distribution scheme	Legend	Nominal voltages
<p>1 Busbars - 1 CB / CIRCUIT</p>	<p>W - busbars; Q₁ - Q₃ – circuit breakers; S₁, - S₃ – separators.</p>	<p>110 kV</p>
<p>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</p>		

recommended where the availability is very high.

Schemes with two busbars systems:

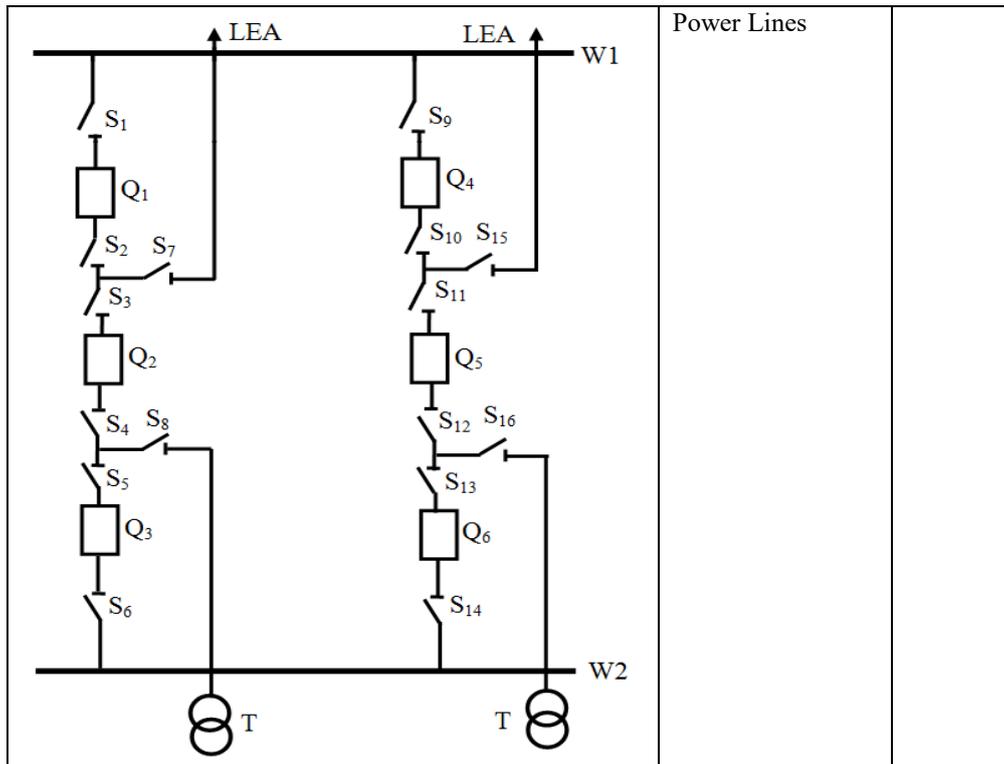
Diagram with two busbars systems with 1 CB - circuit breaker

Name / Distribution scheme	Legend	Nominal voltages
<p style="text-align: center;">2 Busbars - 1 CB / CIRCUIT</p>	<p>W1, W2 - busbars; Q₁ - Q₃ - circuit breakers; S₁ - S₈ - separators;</p>	<p>400 kV 220 kV 110 kV</p>
<p>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.</p>		

Diagram with two busbar systems with 1,5 CB - circuit breakers

Name / Distribution scheme	Legend	Nominal voltages
<p style="text-align: center;">2 Busbars – 1,5 CB / CIRCUIT</p>	<p>W1, W2 - busbars; Q₁ - Q₆ - circuit breakers; S₁ - S₁₆ - separators; T - power transformers; LEA - Overhead</p>	<p>1100 kV 750 kV 400 kV</p>

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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.

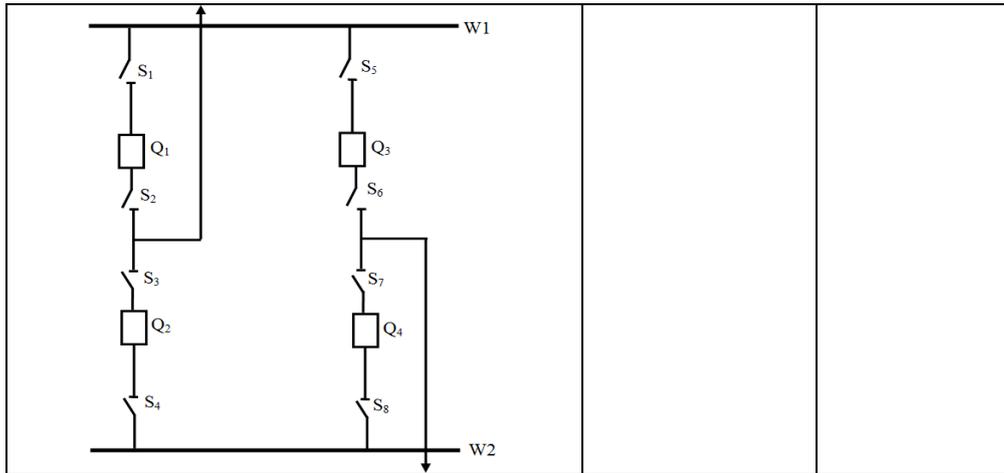
However, the high cost of achieving protections and quick automatic reconnection remains a disadvantage, as the middle switch must operate independently in each of the directions of the two departures.

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

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<p>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.</p>		

Schemes with transfer busbars:

Diagram with double busbars system, U-linking of bars, with transfer bars

Name / Distribution scheme	Legend	Nominal voltages
<p>MAIN COLLECTOR BUSBARS AND TRANSFER COLLECTOR BUSBARS</p>	<p>Scheme composition: W₁ - main busbars; W₂ - transfer busbars; Q₁, Q₃ - circuit breakers; S₁, S₈ - separators;</p>	<p>400 kV 220 kV</p>
<p>When maintenance work is required, the transfer busbars are supplied by closing the circuit breaker Q₂, and the separators S₄ and S₅. 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.</p>		

2.3.2. Wiring diagrams without busbars
Polygon scheme (ring)

Name / Distribution scheme	Legend	Nominal voltages
<p>SCHEME WITH POLYGONAL SYSTEM, WITHOUT COLLECTOR BUSBARS</p>	<p>Q₁ - Q₄ – circuit breakers; S₁, - S₁₂ - separators; T₁, T₁₂ - power transformers; LEA₁, LEA₂ - Overhead Power Lines.</p>	<p>1100 kV 750 kV 400 kV 220 kV</p>
<p>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 the case of the schemes presented:</p> <ul style="list-style-type: none"> - 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. <p>Among the disadvantages of polygonal schemes can be mentioned:</p> <ul style="list-style-type: none"> - 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
<p>SCHEME WITH TYPE H SYSTEM - SUPERIOR, WITHOUT COLLECTOR BUSBARS</p>	<p>Q₁ - Q₃ – circuit breakers; S₁, - S₄ - separators; T₁, T₂ - power transformers; LEA₁, LEA₂ - Overhead Power Lines.</p>	<p>1100 kV 750 kV 400 kV 220 kV</p>

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<p>The power substation has no busbars.</p> <p>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).</p> <p>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).</p> <p>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.</p>		

Scheme H - lower

Name / Distribution scheme	Legend	Nominal voltages
<p><i>SCHEME WITH H TYPE SYSTEM - LOWER, WITHOUT COLLECTOR BUSBARS</i></p>	<p>Q₁ - Q₃ – circuit breakers;</p> <p>S₁, - S₉ - separators;</p> <p>T₁, T₂ - power transformers;</p> <p>LEA₁, LEA₂ - Overhead Power Lines.</p>	<p>1100 kV</p> <p>750 kV</p> <p>400 kV</p> <p>220 kV</p>
<p>The power substation has no busbars.</p> <p>- 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 -</p>		

- 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.

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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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