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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]

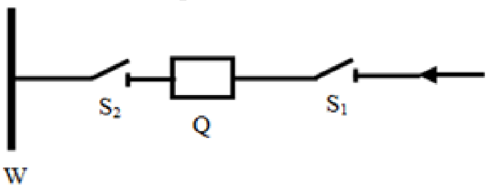

Fig.1. Power line arrival cell (simple busbars)

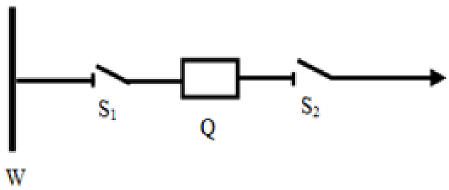

Fig.2. Power line departure cell (simple busbars)

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]

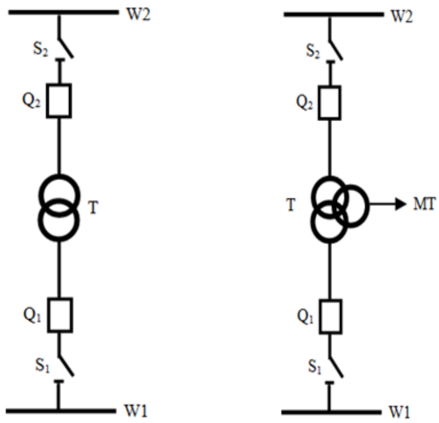

Fig.3. Transformer / autotransformer cells

W1 - 400 kV busbars;
W2 - 220 kV busbars;
S_1, S_2 - separators;
Q_1, Q_2 – circuit breakers;
T - transformer.

W1 - 400 kV busbars;
W2 - 220 kV busbars;
S_1, S_2 - separators;
Q_1, Q_2 – circuit breakers;
T - transformer, which outputs on the tertiary 20 kV.

2.2.3. Coupling Cells:

- *Longitudinal;*
- *Transversal;*
- *Combined.* [7]

a) Longitudinal coupling type 1 (automatic)

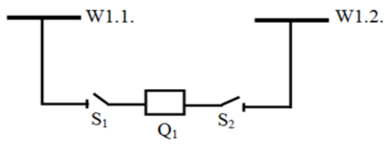

Fig.4. Longitudinal coupling type 1 (automatic)

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) Longitudinal and bypass coupling type 1 :

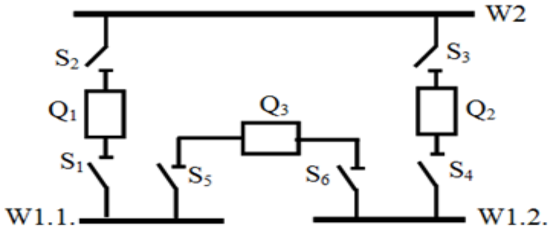

Fig.5. Longitudinal and bypass coupling type 1

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) Longitudinal and bypass coupling type 2 :

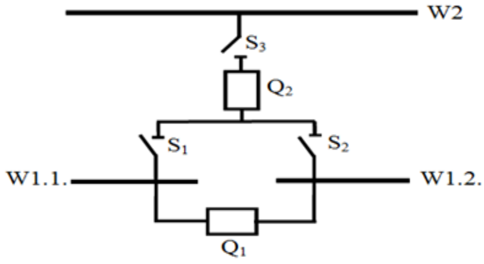

Fig.6. Longitudinal and bypass coupling type 2

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 :

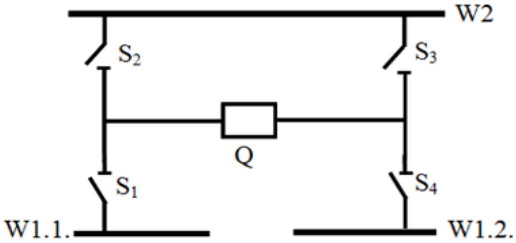

Fig.7. Longitudinal and bypass coupling type 3

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 :

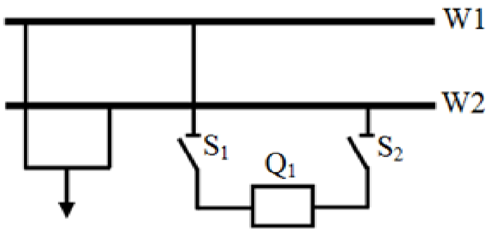

Fig.8. Transverse coupling

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]

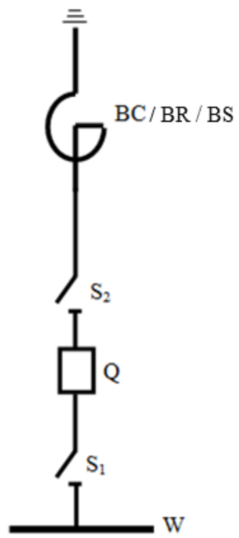

Fig.9. Coil cell
W - busbars; S_1, S_2 - separators; Q – circuit breaker;
BC - compensation coil; BR - reactance coil; BS - extinguishing coil;

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].

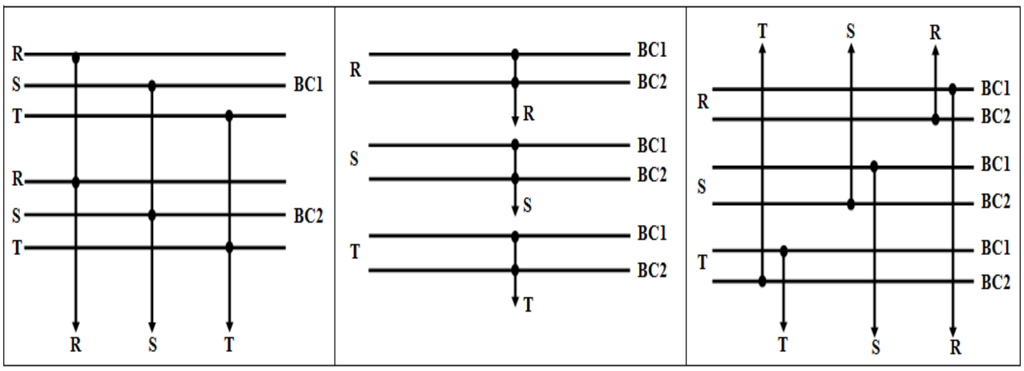

Fig.10. Ways of arranging the phases in an power substation
a - associated phases b - separate phases c - mixed phases

2.4. Types of busbars

2.4.1. Simple busbars (not sectioned):

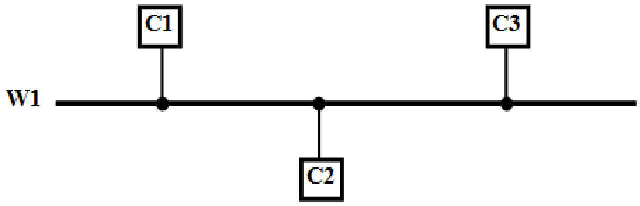

Fig.11. Simple busbars unsectioed
W1 - simple busbars system;
C1, C2, C3 - power cells connected to busbars.

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:

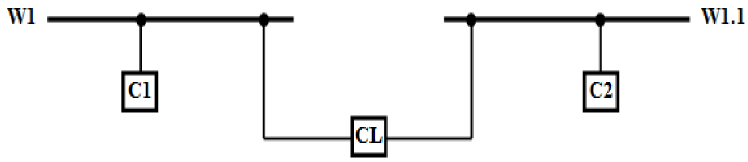

Fig.12. Simple busbars longitudinally sectioned
W1; W1.1. - simple busbars system cut longitudinally;
C1, C2 - electrical cells connected to busbars;
CL - longitudinal coupling.

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:

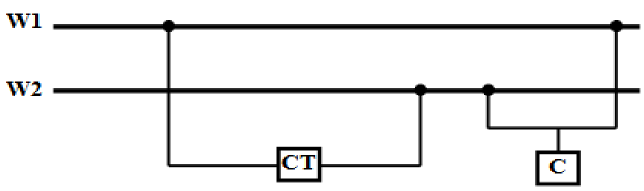

Fig.13. Simple cross - sectioned busbars type 1
W1; W2 - simple unconnected busbars systems;
CT - transverse coupling,
C - power cell.

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:

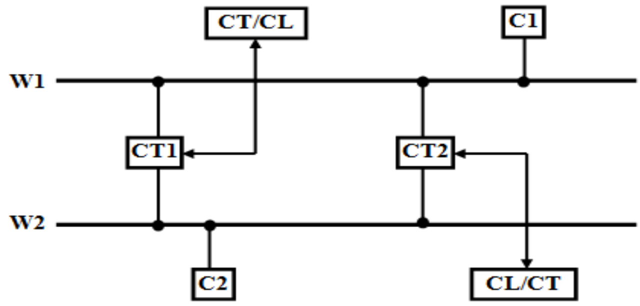

Fig.14. Sectioned longitudinally and bypass busbars
W1, W2 - non-dissected busbars system;
CT1, CT2 - transverse couplings;
CT / CL - transformer cell and / or line cell;
CL / CT - cell line and / or transformer;
C1, C2 - other power cells connected to busbars.

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:

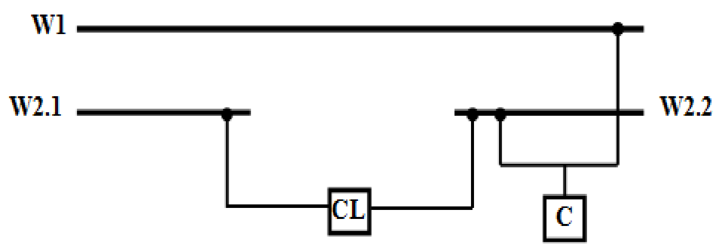

Fig.15. System, a simple one not sectioned and a simple one sectioned longitudinally busbars
W1 - simple non-dissected busbars system;
W2.1 .; W2.2. - simple busbar system cut longitudinally;
CL - longitudinal coupling;
C - power cell.

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:

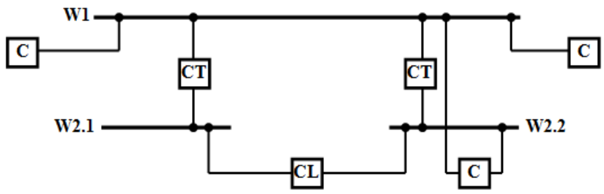

Fig.16. Longitudinally sectioned busbars system with type 1 bypass busbars

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:

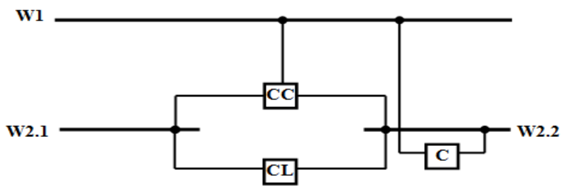

Fig.17. Longitudinally sectioned busbars system with type 2 bypass busbars
W1 - busbars with bypass; W2.1. - W2.2. - double sectioned busbars system;
CC - combined torque (long-transverse);
C - power cell.

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:

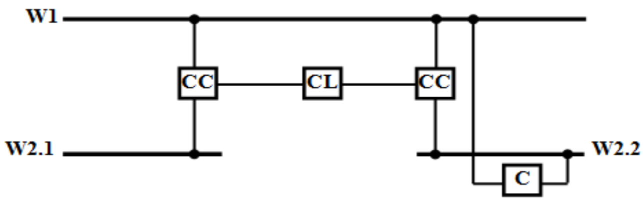

Fig.18. Longitudinally sectioned busbars system with type 3 bypass busbars
W1 - busbars with bypass; W2.1. - W2.2. - double sectioned busbars system;
CC - combined couplings (long-transverse);
CL - longitudinal coupling;

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:

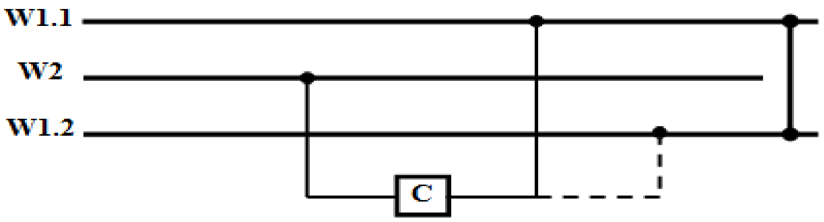

Fig.19. Double unconnected busbars system – U-linking of bars
W1.1 - W1.2 - double system of unsected busbars - U-linking of busbars;
W2. – Simple busbars not dissected;
C - power cell.

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

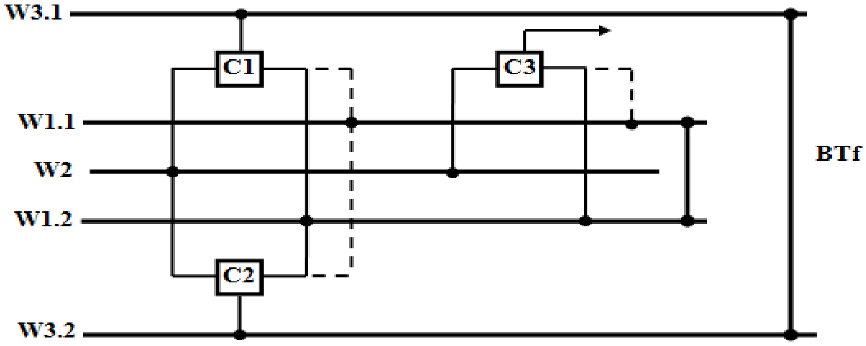

Fig.20. Double system of unconnected busbars - U-linking of the busbars with transfer busbars
W1.1. - W1.2. - double system of unsected busbars - U-linking of busbars;
W2. - Simple busbars not dissected;

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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