Original Article

Digital Transformation in Power Systems: Smart Grid Components, Control, and Challenges

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Abstract: The transformation of traditional electric power systems is essential to meet increasing demands for reliability, efficiency, and sustainability. Conventional grids, built on electromechanical foundations, suffer from limited real-time monitoring, insufficient automation, and inefficiencies in balancing power generation and consumption. This study evaluates the potential of smart grid technologies to address these challenges by modernizing power infrastructure through reactive power compensation, network symmetry, smart substations, and advanced control systems. Using a qualitative-analytical approach, a comparative review of traditional and smart grid systems is conducted, supported by technical assessments of components such as SCADA/DMS platforms, FACTS devices, phase-shifting transformers, and Volt/VAR control systems. Results show that smart grid technologies significantly improve operational efficiency, phase balance, and system stability, while enabling real-time decision-making and integration of distributed energy resources. Smart substations provide enhanced fault detection, automated control, and voltage regulation compared to conventional systems. The study concludes that integrating intelligent digital systems into the grid architecture effectively addresses legacy grid shortcomings. These findings emphasize the urgency of accelerating smart grid deployment worldwide. Policy recommendations include prioritizing investments in smart grid infrastructure, developing supportive regulatory frameworks, and facilitating the transition to sustainable energy models. Future research should focus on quantitative impact evaluations, cybersecurity issues, and cost-benefit analyses of smart grid adoption in diverse regional settings.

Keywords: Smart Grid Technologies, Power System Modernization, Distributed Energy Resources

1. Introduction

In today's context, the rational use of electrical energy, enhancement of energy efficiency, dynamic monitoring of unit energy consumption, and effective management of the processes from large-scale energy production to end-user consumption remain among the most pressing issues in the energy sector. The development and implementation of scientific methods within Smart Grid technologies offer effective solutions to these challenges (Fang et al., 2012; Massoud Amin & Wollenberg, 2005). However, several scientific problems related to smart grid systems remain unresolved and continue to be relevant. This paper briefly introduces the Smart Grid concept, analyzes its current state, key achievements, and persisting

scientific issues. A Smart Grid is a system that integrates digital technologies, smart devices, and bidirectional communication mechanisms across the entire process from energy generation to end-user delivery (Ekanayake et al., 2012; Lo & Ansari, 2011; Reka & Dragicevic, 2018). The primary goal of this system is to ensure reliable, efficient, resilient, and sustainable delivery of electricity.

The increasing demand for electric energy and the need for its efficient management requires the development of modern control systems. Smart grids meet these emerging demands by operating similarly to conventional power grids, but with the critical distinction of real-time monitoring, control, and data processing capabilities enabled by digital technologies (Gungor et al., 2011; Siano, 2014). In this system, electrical energy flow is not unidirectional (top-down) as in traditional systems, but rather decentralized, enabled by various geographically distributed sources. The energy produced is distributed equally across the grid. Electricity is no longer generated solely by large-scale power plants, but also through renewable energy sources such as solar and wind power. Moreover, surplus energy can be fed back into the grid. This entire process is carried out through the structural components of the smart grid system (see Figure 1).
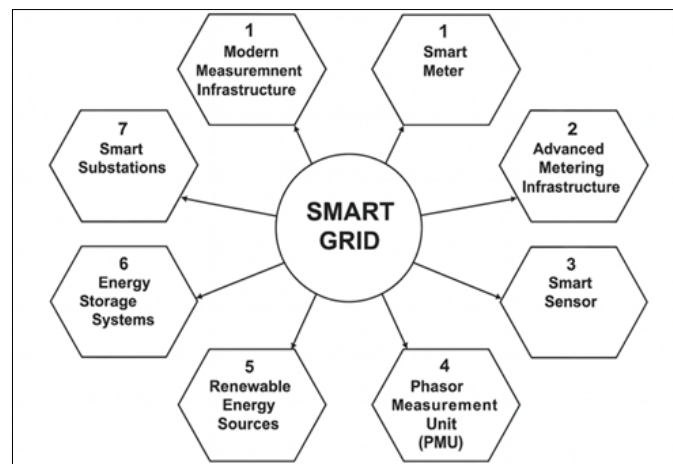

Figure 1. Components of the Smart Grid

2. Literature Review

The concept of the Smart Grid has been extensively explored in both theoretical and applied research over the past two decades. Numerous studies have identified the limitations of traditional power systems, particularly their lack of real-time monitoring, one-way energy flow, and vulnerability to faults (Amin, 2011; Bedi et al., 2018; Ilic et al., 2005; Pfenninger et al., 2014). In response, smart grid technologies have emerged as a transformative solution, integrating advanced digital infrastructure, bidirectional communication, and automation to address these longstanding challenges. Traditional power grids were designed for centralized generation and passive consumption, wherein electricity flows linearly from large-scale power plants to end-users. While this model served global energy demands for much of the 20th century, it is increasingly inadequate in the face of modern energy challenges. Rising electricity consumption, the integration of renewable energy sources, ageing infrastructure, and the need for energy efficiency demand a more intelligent and responsive system. Moreover, climate change imperatives and the global push toward decarbonization have further accelerated the urgency for grid modernization.

Smart Grids represent a paradigm shift in the operation and management of electricity networks. At their core, Smart Grids leverage information and communication technologies (ICT), advanced metering infrastructure (AMI), sensor networks, and distributed energy resources (DERs) to enable a more dynamic, adaptive, and resilient power system (Al-Shetwi et al., 2024; Khalid, 2024; Kumari & Tyagi, 2024). Through real-time data acquisition and analytics, operators can monitor and control grid operations more efficiently, detect and isolate faults automatically, and optimize energy flow based on current demand and supply conditions. This not only enhances the reliability and security of the electricity supply but also improves energy efficiency and reduces operational costs. One of the most significant advancements brought about by Smart Grids is the bidirectional flow of energy and information. Consumers are no longer passive recipients but can actively participate in the energy ecosystem as "prosumers" who generate, store, and even sell energy back to the grid. This decentralization facilitates greater integration of renewable energy sources such as solar photovoltaics and wind power, contributing to sustainability goals and reducing

dependency on fossil fuels. Additionally, demand-side management becomes more viable, allowing utilities to implement dynamic pricing schemes and consumers to adjust their consumption patterns accordingly.

Another key component of Smart Grids is automation, which enables self-healing capabilities and minimizes human intervention in routine or emergency operations. Automated substations, intelligent circuit breakers, and distributed control systems allow for rapid response to disturbances, thereby enhancing grid resilience. Cybersecurity, although a growing concern, is also an integral element of Smart Grid design, as the increased reliance on digital infrastructure necessitates robust protection against cyber threats. The transition from conventional power systems to Smart Grids marks a critical evolution in the energy sector. This transformation not only addresses the technical inefficiencies of legacy systems but also aligns with broader societal goals such as sustainability, energy equity, and climate resilience. As countries continue to modernize their energy infrastructure, the deployment of Smart Grid technologies will play a pivotal role in shaping the future of energy systems worldwide (Rehtanz & Hassan, 2013); (Power & Society, 2011).

Prior literature has consistently emphasized the multifaceted benefits of Smart Grids in enhancing grid reliability, improving energy efficiency, and strengthening overall system resilience. These advantages stem from the ability of Smart Grid systems to manage energy flows intelligently, adapt to changing demand conditions, and respond effectively to disruptions. The transition from conventional grids to smart networks represents more than a technological upgrade—it signifies a shift toward a more sustainable, flexible, and user-interactive energy infrastructure. Numerous studies have explored the technological enablers of Smart Grids, delineating how their integrated architectures contribute to operational enhancements across transmission and distribution networks. Tutorials Point and similar technical sources provide accessible overviews of the foundational architecture of Smart Grids, outlining key components such as smart meters, Supervisory Control and Data Acquisition (SCADA) systems, Flexible AC Transmission Systems (FACTS), and Volt/VAR control devices. These elements form the core technological backbone of modern Smart Grids. For instance, smart meters enable real-time monitoring of electricity consumption at the consumer level, facilitating both demand-side management and time-of-use pricing.

SCADA systems allow operators to monitor and control the grid infrastructure remotely, enhancing situational awareness and reducing response times during faults or disturbances (Enemosah & Chukwunweike, 2022; Nuruzzaman & Rana, 2025; Sayed & Gabbar, 2017). Similarly, FACTS devices, including Static VAR Compensators (SVCs) and Unified Power Flow Controllers (UPFCs), offer advanced capabilities for regulating voltage levels, managing reactive power, and optimizing power flow. Volt/VAR control systems, meanwhile, automate the fine-tuning of voltage and reactive power to ensure grid stability and minimize energy losses. Beyond these foundational components, academic literature accessible through databases such as Google Scholar expands the focus to include high-level technologies like phase-shifting transformers (PSTs), smart substations, and High Voltage Direct Current (HVDC) systems. PSTs are instrumental in redirecting power flows to balance system loads, while smart substations enhance grid automation through digital relays, intelligent electronic devices (IEDs), and real-time communication protocols. HVDC systems, known for their efficiency in long-distance power transmission, are increasingly integrated into smart grid frameworks, especially for interconnecting renewable energy sources in remote areas.

While prior research often isolates these technologies to examine their functions and benefits, this article takes a more integrative and holistic perspective. It synthesizes key insights from existing studies to evaluate not only the components themselves but also the broader challenges associated with smart grid implementation. These challenges include interoperability, cybersecurity, regulatory frameworks, and the high initial cost of infrastructure deployment. Moreover, this paper explores how advanced control strategies, such as the deployment of FACTS technologies, the implementation of Advanced Metering Infrastructure (AMI), and integration of SCADA with Distribution Management Systems (DMS), can be used in concert to achieve optimal performance. By bridging theoretical knowledge with practical application, this article contributes to a more comprehensive understanding of how smart grids function as interconnected systems. The integrative analysis presented herein highlights the necessity of coordinated technological deployment and policy support to fully realize the transformative potential of Smart Grids in the global energy landscape (Tripathy et al., 2017; Yi Wang et al., 2015). Thus, this study builds upon existing studies by providing a structured overview of smart grid components, comparing them to traditional grids, and proposing modern, adaptive solutions tailored to current energy demands.

3. Materials and Methods

This study applies a qualitative analytical approach that combines a review of recent literature with schematic and functional analysis of smart grid components. Technical diagrams and block structures of

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Smart Grid systems, including Volt/VAR processors, phase-shifting transformers, smart substations, and power flow control schemes, were examined to illustrate operational principles. A comparative evaluation between traditional and smart grid systems was conducted using a feature-based tabular method. The analysis focused on digital technologies such as SCADA, AMI, FACTS devices, and intelligent electronic devices (IEDs), drawing on academic publications, technical documentation, and industry standards.

4. Results and Discussion

Smart Grid is a modern energy system composed of several integrated components, including smart meters, advanced metering infrastructure, intelligent sensors, pharos measurement units (PMUs), renewable energy sources, energy storage systems, smart substations, and digital measurement infrastructure. Together, these elements ensure the efficient, secure, and sustainable delivery of electrical energy. One of the essential features of the smart grid is its capability for bidirectional communication and energy storage integration. This means the system can simultaneously manage and transmit energy from both conventional power plants and decentralized renewable sources. The bidirectional communication facilitates real-time data exchange between producers and consumers, enabling dynamic monitoring and control of energy flows. In contrast to traditional top-down energy distribution systems, the smart grid enables decentralized power generation from various geographically distributed sources. The total generated energy is evenly distributed across the network. Electricity is no longer produced solely by large-scale stations but also through renewable sources such as solar and wind. In some cases, surplus energy can even be fed back into the grid. However, such integration introduces various technical and management challenges. To address these, smart grid technologies offer modern, digital, and adaptive solutions, ensuring the reliable and efficient operation of future power systems.

Table 1. A comparative analysis of traditional power grids and smart grid systems

Feature	Traditional Power Grid	Smart Grid
Technology	Electromechanical: Traditional energy infrastructure is based on electromechanical systems, typically involving manual or electrically driven mechanical devices. It lacks integrated communication and internal control systems.	Digital: Modern smart grids use digital technologies that enhance communication between devices, enable remote control, and support self-regulating functions.
Distribution	Unidirectional Distribution: Electricity flows in one direction—from the main power station to the consumer.	Bidirectional Distribution: Electricity can flow both ways. Consumers with renewable sources (e.g., solar panels) can also feed energy back into the grid.
Sensors	Few Sensors: Traditional grids are not equipped for extensive sensor deployment, making fault detection difficult and prolonging outages.	Sensor-Rich Networks: Smart grids feature numerous sensors throughout the network, enabling quick fault detection and energy rerouting and reducing affected zones during outages.
Monitoring	Manual Control: Due to infrastructure limitations, monitoring and controlling power distribution must be done manually.	Automated Self-Monitoring: Smart grids use digital tools to monitor loads autonomously, detect outages, and manage distribution efficiently.
Device Resilience	Failures and Blockages: Ageing and limited infrastructure lead to frequent failures, potentially disrupting supply to end-users.	Flexible Operation: Smart grids can reroute electricity around problem areas, minimizing outages at the consumer level.

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Control	Limited Control: Once electricity leaves the station or substation, energy providers have little control over distribution.	Extensive Control: Thanks to sensors and modern infrastructure, providers can monitor and manage the entire energy flow, from generation to end-user.
Customer Choice	Limited Options: Traditional grids do not offer consumers flexibility in how they receive electricity.	Greater Options: Smart grid infrastructure supports multiple providers and allows integration of alternative energy sources, enhancing consumer participation and choice.

Table 1 provides a comprehensive comparison between traditional power grids and modern smart grid systems, highlighting significant differences across several critical features such as technology, distribution, sensing, monitoring, resilience, control, and consumer engagement. Traditional power grids primarily rely on electromechanical technologies, consisting of legacy infrastructure such as mechanical switches and analog meters. These systems lack integrated digital communication, making them less efficient in terms of operational control and real-time responsiveness. In contrast, smart grids leverage digital technologies that enable seamless communication between devices, support automated control mechanisms, and incorporate self-regulating functions, drastically improving grid intelligence and responsiveness. In terms of electricity distribution, conventional grids operate on a unidirectional model, where power flows solely from centralized generation facilities to consumers. This rigid structure limits the ability of consumers to participate in energy generation. On the other hand, smart grids support bidirectional energy flow, allowing end-users, particularly those who utilize renewable energy systems such as solar panels, to not only consume electricity but also contribute surplus energy back into the grid. This capability promotes decentralization and enhances energy democratization.

When considering sensor deployment, traditional grids include minimal sensing capabilities, which hampers real-time fault detection and can result in prolonged service interruptions during outages. In contrast, smart grids are rich in sensor networks, enabling rapid detection of anomalies, automatic isolation of faulty segments, and rerouting of electricity to maintain system reliability and service continuity. This also supports automated self-monitoring processes that replace the manual monitoring and control required in older grids, leading to faster and more accurate responses to changes in demand and supply. In terms of resilience and flexibility, the ageing infrastructure of traditional grids often results in frequent system failures and power outages, with limited ability to isolate and manage disruptions. Smart grids, however, are designed for adaptive and flexible operations. They can dynamically reroute electricity around malfunctioning components, thereby reducing the impact of outages and enhancing service reliability.

Regarding control capabilities, energy providers in traditional systems have limited post-substation control, making it difficult to manage supply based on real-time demand or grid conditions. Conversely, smart grids offer comprehensive end-to-end control, facilitated by advanced software and integrated communication technologies, allowing energy providers to actively monitor, manage, and optimize energy flows throughout the entire network. Finally, concerning customer participation, traditional grids offer little flexibility or choice, as consumers typically depend on a single energy provider and have no control over the source or type of energy they receive. Smart grids, by contrast, foster greater consumer choice and participation by supporting multi-provider environments, enabling the integration of distributed energy resources (DERs), and promoting energy efficiency initiatives such as demand response and time-of-use pricing. This empowers consumers to make more informed energy decisions and participate in energy markets, contributing to a more sustainable and resilient energy ecosystem. In addition, the study analyzes existing problems commonly encountered in power networks and presents key solutions. One of the most pressing issues is reactive power compensation. To address this challenge, the smart grid offers several modern solutions. Specifically, it utilizes Flexible AC Transmission Systems (FACTS) to mitigate faults and disturbances in the network. There are three primary methods of power flow control employed within this approach:

1.   STATCOM – Synchronous Static Compensators.
2.   SVC – Static VAR Compensators.
3.   UPFC – Unified Power Flow Controllers

These technologies enable simultaneous control of power flow and voltage across the network. They operate based on Voltage Source Inverters (VSI), allowing for real-time regulation of voltage, phase angle, and power flow (see Figure 2).
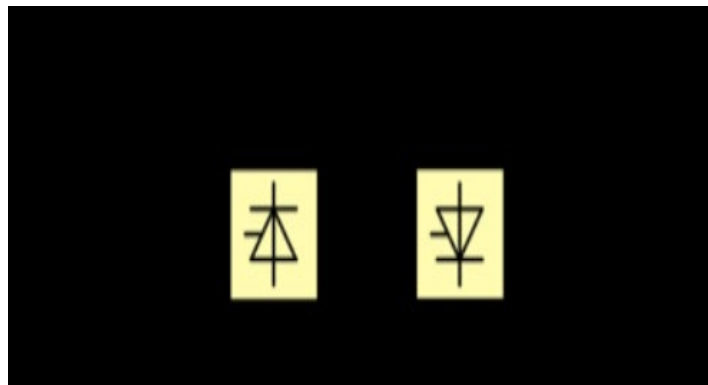

Figure 2. Schematic diagram of power flow control in smart grid systems

Figure 2 illustrates a schematic diagram of power flow control in smart grid systems, showcasing the role of power electronic converters in enabling flexible and efficient electricity transfer between two AC buses. In this configuration, two alternating current (AC) systems, labeled as AC Bus 1 and AC Bus 2, are interconnected through a back-to-back converter arrangement consisting of a rectifier and an inverter. The rectifier converts AC power from Bus 1 into direct current (DC), which is then transmitted through a DC link to the inverter. The inverter subsequently converts the DC power back into AC to supply Bus 2. This AC–DC–AC conversion system enables precise and independent control of power flow between the buses, allowing for regulation of voltage, frequency, and phase angle. Such configurations are essential in modern smart grids for enhancing power quality, enabling bidirectional energy flow, and integrating renewable energy sources. By decoupling the two AC systems, this arrangement provides the flexibility to control real and reactive power dynamically, contributing to grid stability and resilience. Applications of this system are commonly found in smart substations, microgrid interfaces, and Flexible AC Transmission Systems (FACTS), such as STATCOMs, Unified Power Flow Controllers (UPFC), and High Voltage Direct Current (HVDC) systems. Overall, the diagram represents a core mechanism for intelligent power management in advanced grid infrastructures.

In this scheme, series and parallel inverters serve as the primary devices. The series inverter is responsible for controlling power flow by injecting additional voltage into the transmission line. It introduces a controllable voltage both in phase and amplitude into the system, which enables the regulation of power flow direction by either increasing or decreasing the line power transfer. The parallel inverter, on the other hand, is used to ensure voltage stability within the network. It monitors the voltage level in the grid and directly injects or absorbs reactive power, thereby maintaining voltage at the desired level. When the voltage drops and falls below the required threshold, the parallel inverter supplies reactive power to the grid. This additional reactive power helps raise the voltage level, as reactive power is one of the key factors affecting voltage magnitude. One of the advanced solutions in this domain is the implementation of the Volt/VAR Processor (VVP) system, which provides automated voltage and reactive power control.

Figure 3 shows the functional diagram of the Volt/VAR processor system. The figure indicates that the system enables precise control of both voltage and reactive power. Through this capability, it becomes possible to maintain voltage at a stable level and reduce losses in the network by effectively managing reactive power. To achieve this, the smart grid employs a Volt/VAR control system, which consists of various components, including a Volt/VAR processor, voltage regulators, capacitor banks, AMI-based measurement systems, load tap changers (LTCs), and smart inverters. Within this framework, the Volt/VAR processor functions as the central control unit, activating all system components. It receives input signals from LTCs and adjusts transformer voltage accordingly. The capacitor bank controller manages reactive power by automatically connecting or disconnecting capacitor banks to or from the network. The AMI (Advanced Metering Infrastructure) provides continuous feedback on voltage level fluctuations to the Volt/VAR system. Smart inverters monitor the behavior of renewable energy resources and synchronize them with the grid. Collectively, these components allow for enhanced energy management and system optimization.
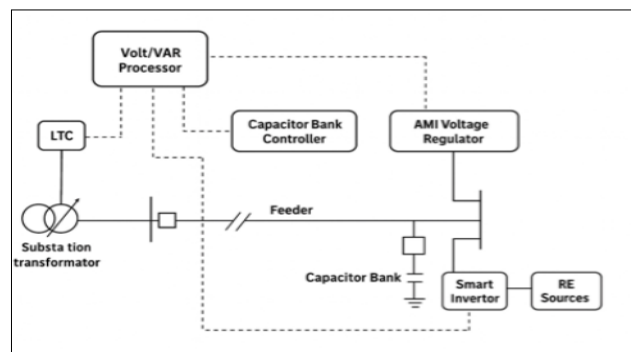
Figure 3. Functional diagram of the Volt/VAR processor system

Electricity is typically transmitted over long distances through power lines, which leads to significant energy losses. Smart grid technologies help reduce such losses, particularly through the application of High Voltage Direct Current (HVDC) technology, which increases transmission efficiency. In this approach, the alternating current (AC) produced at a power plant is converted into direct current (DC) using specialized converters before transmission. DC transmission significantly reduces power losses, especially over long distances. HVDC systems generally operate at voltages ranging from 100 kV to 800 kV. In addition, renewable energy sources such as solar and wind are often deployed near the point of consumption, which reduces the need for long-distance energy transmission and further improves system efficiency. Modern software systems such as AMI and SCADA (Supervisory Control and Data Acquisition) are employed to monitor energy flow and grid status in smart grids effectively. These systems track network changes in real time and can issue automated control commands when necessary.

In traditional energy systems, electricity distribution is typically managed through basic substations. In smart grids, however, this role is fulfilled by intelligent substations, which not only distribute power but also continuously monitor system conditions. These substations can detect faults in advance and enable proactive, efficient control. One of the core components of automation in smart grids is the smart substation. A smart substation is a modern, digitized version of a traditional substation, integrating automation technologies into conventional power distribution infrastructure. These substations provide real-time monitoring of power distribution, enable line protection, enhance power quality, and allow for voltage adjustment. Smart substations are composed of advanced technological devices and equipment (see Figure 4).
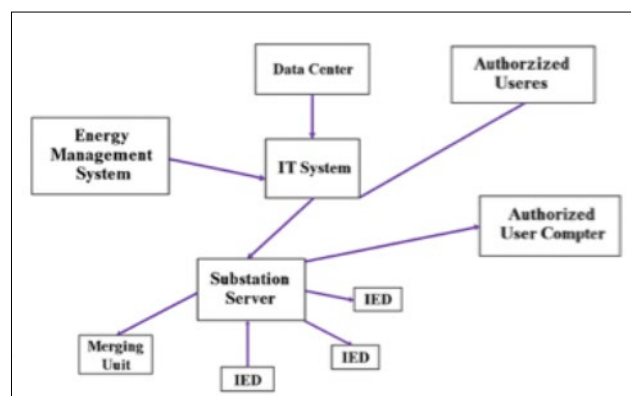

Figure 4. Main components of Smart substation architecture

Smart substation automation refers to the automation of various operations within an electrical system, such as switching, control, monitoring, and protection, which collectively contribute to establishing a highly reliable, efficient, and secure power substation. This process is implemented using Intelligent Electronic Devices (IEDs), the SCADA system (Supervisory Control and Data Acquisition), Remote Terminal Units (RTUs), and Programmable Logic Controllers (PLCs). Additionally, the Human-Machine Interface (HMI) serves as a graphical communication interface for substation operators, enabling effective interaction with the system. The general configuration of these substations typically consists of three hierarchical levels (see Figure 5).
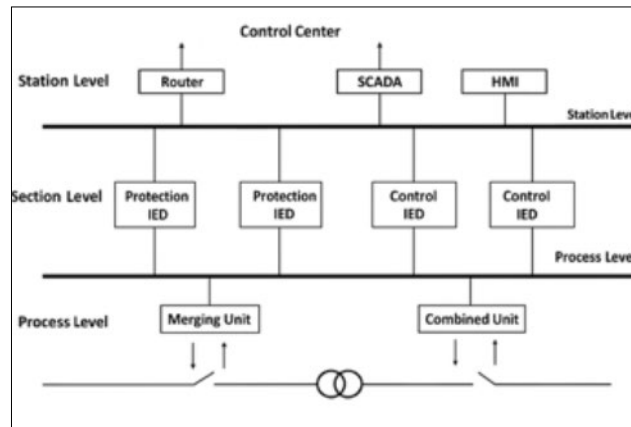
Figure 5. Hierarchical configuration of a smart substation

Automating substations significantly enhances the reliability of the electrical power system, as faults can be detected and isolated more rapidly. This reduces the need for human intervention, thereby minimizing the likelihood of human errors. All these processes are monitoring, control, and operation—are managed by the SCADA (Supervisory Control and Data Acquisition) and DMS (Distribution Management System) platforms. In the context of effective power flow management within the energy system, maintaining phase symmetry is of particular importance. This is because the power in each phase must be equally distributed to ensure balance. The smart grid addresses this requirement using specific technologies that characterize the relationship between voltage and time. Preserving phase symmetry and avoiding imbalances are critical for ensuring efficient power delivery. This is achieved through adjustment of the phase angle, which is carried out by phase-shifting transformers in smart grids. The structural configuration of these transformers is illustrated in Figure 6.
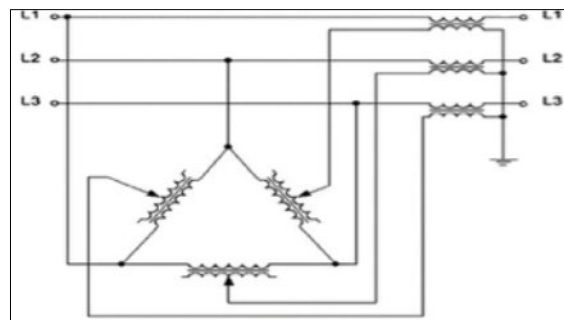

Figure 6. Structural types of phase-shifting transformers

A phase-shifting transformer consists of two main components: a shunt transformer and a series transformer. The shunt transformer is connected in parallel to the network and generates an output voltage that is phase-shifted by 90° (in quadrature) relative to the line voltage. The secondary terminals of the shunt transformer are connected to the input terminals of the series transformer. The secondary winding of the series transformer is connected in series with the transmission line phases. As a result, the quadrature component produced by the shunt transformer is added to the transmission line voltage through the series transformer. The voltages from the network and the phase-shifting transformer are combined geometrically, meaning their vector sum is calculated by taking the angle between them into account. The resulting voltage thus forms with a modified phase angle. Through this vector summation, it becomes possible to adjust the phase angle of the transmission line's output voltage. These devices enable the preservation of phase symmetry in the network and allow for precise control of the phase angle. Phase-shifting transformers can be classified into the following types:
- Direct phase-shifting transformer
- Indirect phase-shifting transformer
- Asymmetric phase-shifting transformer
- Symmetric phase-shifting transformer

These classifications are based on the construction and method of implementing the phase shift within the electrical network.

5. Conclusions

This study concludes that integrating modern control technologies into electric power systems is crucial to effectively addressing current challenges. As demand for reliability, efficiency, and sustainability increases, the adoption of smart grid technologies becomes indispensable. Advanced intelligent control systems that offer real-time monitoring and automation significantly improve the management and analysis of electrical networks. Digital technologies enhance precision and operational efficiency throughout the entire energy infrastructure, from generation to distribution. A major technical challenge in traditional grids is maintaining phase symmetry, which is vital for minimizing power transmission losses. The use of phase-shifting transformers allows dynamic adjustment of phase angles, promoting balanced power flow and system stability. Additionally, substations play a key role in delivering electricity to end users. Transitioning to smart substations enhances control and reliability while enabling automated fault detection, voltage regulation, and the integration of distributed energy resources. The deployment of smart technologies, such as Volt/VAR control systems, FACTS devices, and SCADA/DMS platforms combined with smart substations and phase-shifting transformers, offers a comprehensive solution for building a more reliable, efficient, and intelligent power grid. These advancements are essential to meet future energy demands and ensure the sustainability and resilience of modern electric power systems.

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