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Power Generation, Transmission, and Distribution: Principles and Recent Developments

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Abstract

The electric power sector is undergoing a profound transformation driven by the rapid integration of renewable energy sources, widespread deployment of power electronic converters, and increasing digitalisation of power system operation. These changes are reshaping the traditional structure of power generation, transmission, and distribution networks, while introducing new technical and operational challenges related to system stability, protection, planning, and resilience. This review presents a comprehensive overview of the fundamental principles and recent developments across all major layers of modern power systems. Key advancements in renewable generation technologies, grid-forming inverters, energy storage systems, high-voltage direct current transmission, active distribution networks, and microgrids are systematically discussed. In addition, the growing role of digitalisation, artificial intelligence, and digital twin technologies in enhancing system observability, control, and decision-making is examined. The review further highlights emerging challenges in protection, transmission–distribution coordination, and resilience-oriented planning under high renewable penetration. Regulatory frameworks and grid codes are also considered in the context of supporting reliable and sustainable power system evolution. By synthesising recent research and identifying open challenges, this review provides valuable insights for researchers, system planners, and policymakers working toward the development of resilient, low-carbon, and intelligent power systems.

Keywords: Power generation; Power transmission; Power distribution; Renewable energy integration; Grid-forming inverters; Smart grids; Digital twins

1. Introduction

The electric power systems form the basis of the contemporary society since they enable individuals to generate goods and services in factories, to communicate digitally, to access healthcare services, and to conduct their usual household chores. Traditionally, the power system was created as large centrally-located generation systems, one directional power flow, and passive networks of power transportation and distribution. This architecture was once dependable over decades, but it is currently experiencing an outcry as people have raised increasing concerns about electricity as a contributor to climate change and the enormous use of renewable energy sources. These challenges have also caused full revamping of power generation, transmission and distribution infrastructure towards more flexible, smart and robust infrastructure. The recent years have experienced a paradigm shift of rejection of conventional grids which were mainly electromechanical to power-electronic grid with distributed energy resources, advanced control strategies and online monitoring. Not only generation technologies are changing, but also transmission planning, automation of the distribution, and schemes of protection are being changed, along with the philosophy of running systems. Consequently, contemporary power systems are taking the form of complicated cyber-physical networks that demand simultaneous development of all levels of systems.

The worldwide shift to low-carbon energy regimes has been a major boost in the adoption of renewable energy sources like solar photovoltaics and wind turbines. Renewable sources are also interfaced in large quantities by power electronic converters unlike the traditional synchronous generators, which change the dynamic characteristics of power systems. The resources with inverters also present new problems with regard to inertia reduction, voltage stability, and fault response. In order to solve those problems, grid-forming inverter technologies are acquiring more and more popularity as they can actively manage voltage and frequency in systems abundant in renewable resources (Lasseter et al., 2019). Meanwhile, the growth in distributed generation has led to the growth of microgrids, which may be grid-connected or islanded. Not only do microgrids increase the flexibility and resilience of systems, but they also add coordination and protection issues, which are not very similar to conventional networks. The fact that this has remained an open research problem with regard to ensuring a stable and reliable operation under the varying operating conditions of a system, even when the converter-based generation has a high penetration.

Transmission networks are important in facilitating large-scale integration of renewables to power load centres by transferring geographically dispersed generation sites to load centres. This increased incursion of renewables has increased the expansion and strengthening of transmission, done with a high degree of uncertainty regarding demand growth and generation variability. The contemporary planning of transmission should thus entail probabilistic planning, sustainability objectives over a long period, as well as constraints that are policy-driven (Lumbreras & Ramos, 2016). High-voltage direct current (HVDC) power transmission has become one of the technologies for long-distance transmission of power and integration of offshore wind power. HVDC systems based on voltage source converters have new protection and fault control problems, but provide better controllability. Direct current faults have a different behaviour compared to AC faults, and thus, specific approaches to protection are necessary, including fault current limiters as they provide a higher level of system safety and reliability (Chang et al., 2016; Huang et al., 2015).

One such massive change that is being experienced in the distribution systems is that of change towards active distribution systems with two way power flows, distributed generation, and distributed energy storage systems. BESS is a crucial aspect that could be used to accommodate voltage control, frequency control, and congestion at the distribution level. In order to examine the behaviour of the system under distribution networks in active modes, the dynamics of aggregated BESS have to be modeled accurately to allow the possibility to ensure the ability to operate the system (Bahramipanah et al., 2016). However, the increasing complexity of the distribution systems also leads to the problem of protection, fault detection, and observability coordination of the systems. The traditional protection systems are not always adequately applied to the high concentration of distributed resources, and this is why an enormous amount of research is carried out on the adaptive and intelligent protection methods (Memon & Kauhaniemi, 2015).

The revolution of the power system is actively supported by the development of communication technologies and digital infrastructure. Smart grids have low-latency communication networks that are dependable and are used to help monitor, control and automate activities across the system layers in real-time. Several options of communication technologies including wireless, fibre-optic, and hybrid have been suggested to address the various needs of smart grid applications (Emmanuel & Rayudu, 2016). The integration of the communication networks introduce cybersecurity threats and contribute to the interdependence of the system, the significance of efficient system design and coordinated strategies of cyber-physical protection. As the power systems will be more data-driven, an effective communication infrastructure is a condition to achieve situational awareness and operational efficiency.The artificial intelligence (AI) proved to be a powerful tool of addressing the progressively more complicated character of the modern power systems. Tools based on artificial intelligence are increasingly being applied in the optimisation of stability and control, fault detection, and predictive maintenance. The techniques enable making decisions faster and more elasticity in the event of unstable working conditions (Cheng & Yu, 2019). Besides AI techniques, the digital twin technology has also been given attention as a method to generate virtual models of physical power system assets. Digital twins facilitate real-time analysis, scenario testing and managing assets, especially in microgrid environments where operational flexibility is paramount. Digital twins can be linked to control and protection systems to provide new possibilities of improving the reliability and resilience of the system (Andryushkevich et al., 2019).

With the fast-paced change of power generation, transmission and distribution systems, the new systems are in dire need of thorough reviews that will incorporate the background principles with the technological advancements in the recent past. The available literature mainly dwells on individual areas of power systems, like generation technology or smart grid communication, without offering any comprehensive viewpoint. To address this gap, this review will take a systematic approach to reviewing basic principles and new trends in all major areas of the power system. The article dwells upon such recent developments as renewable generation, transmission planning, HVDC systems, active distribution networks, microgrids, digitalisation and intelligent control. This review synthesises reports of developments in the period between 2015 and 2019 to offer an insight into the current issues, enabling technologies, and future research directions of the next-generation power systems.

2. Fundamentals of Electric Power Systems

An electric power system refers to a sophisticated system that is formed with the aim of producing and supplying electrical power to end consumers in an efficient and dependable way. Conventionally, power systems were organised hierarchically, i.e. with centralised generation units, high-voltage transmission systems, and low to medium-voltage distribution systems. This hierarchical model has allowed control and coordination of power flow in predictable operating conditions. Nevertheless, the current power systems are moving towards the trend of decentralisation, more automation, and digitalisation, which are fundamentally changing the structural features of a power system. This trend has emerged due to the growing convergence of distributed sources of energy, which has led to the blur between the transmission and distribution networks, and where a previously passive distribution system has been turned into an active participant in the system's operation. Such transformations require more insight into the fundamentals of a system to provide the stability, reliability, and efficiency of the system in all its operating conditions. Figure 1 illustrates the overall architecture of a modern power system integrating generation, transmission, distribution, and digital control layers.

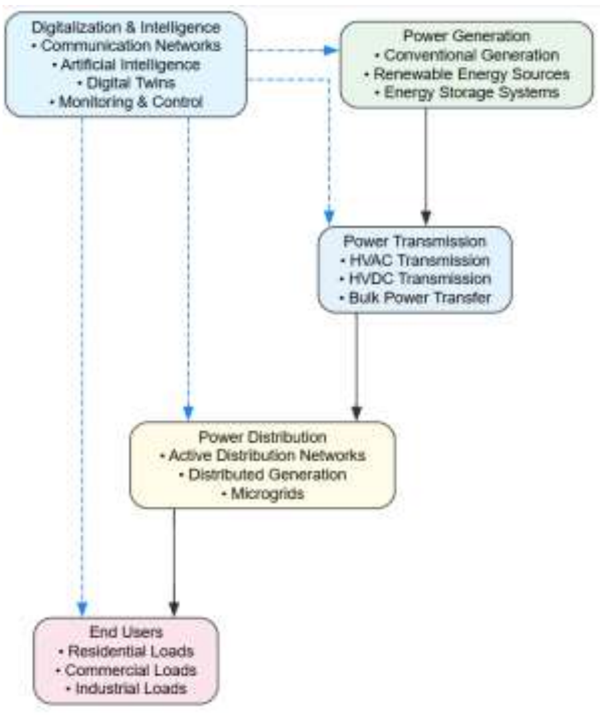

Figure 1. Overall Architecture of a Modern Power System

The analysis of power flow is a major consideration in the operation and planning of power systems. It entails the calculation of voltages, phase angles and power flows across the network in steady-state situations. Proper power flow solutions are needed in the operational decision-making, contingency analysis, and the planning of system expansion. With the increased decentralisation and dynamism in the systems, it has become a challenge to ensure sufficient system observability. The state estimation is vital in improving system observability by offering a real-time estimate of system states with restricted and frequently noisy measurements. The following are a few of the issues that should be handled in state estimation in smart distribution systems: sparse measurement infrastructure, extreme variability of distributed generation and bi-directional flows of power. The challenges require sophisticated estimation methods that will be able to work dependably in cases of uncertainty and data limitations (Dehghanpour et al., 2018).

Electric loads do not have uniform temporal and spatial characteristics, which have a strong impact on the behaviour of power systems. Conventional power systems viewed loads as passive and uncontrollable components, but in contemporary systems, loads are now being used to exploit load flexibility to improve operational efficiency. Demand response programs allow consumer to modify their electricity demand in reaction to price inputs or system conditions in sustaining peak shaving, congestion control and frequency regulation. When many residential appliances are aggregated, system operators can enjoy a great deal of flexibility without interfering with the comfort of the user. These aggregation structures are based on concerted control measures, communication infrastructure to deal with heterogeneous loads. Modelling and controlling aggregated demand is a prerequisite to the modern power system operation, especially those with high renewable content (Elghitani and Zhuang, 2017).

The transmission systems have the role of transporting bulk electrical power at a significant distance with minimal losses and system stability. Decades of experience have seen high-voltage alternating current (HVAC) transmission as the most preferred technology, since it is simple and synchronous generators can be used to produce it. The HVAC systems are however, limited in terms of the reactive power management, stability limitations and line charging effects, particularly with long distances. In order to address these shortcomings, high-voltage direct current (HVDC) transmission has arisen as an acceptable alternative in long-range and large-capacity power transmission. Multi-terminal HVDC systems take the functionality of point-to-point HVDC links by facilitating the ability to exchange power between more than two nodes. Fault isolation and system protection in such networks is tied to the integration of novel DC circuit breakers, including resonant semiconductor breakers (Kinjo et al., 2018).

Distribution systems provide an interface between the bulk power system and the end users. Conventionally structured in such a way that power flows in only one direction, distribution networks are now having to consider distributed generation, energy storage, and electric vehicles. These transformations pose problems of working in terms of voltage, and coordination of protection as well as system stability. Microgrids are a localised grouping of loads and distributed resources that can or cannot interact with the main grid and can interact on their own. Microgrids have hierarchical control structures which permit the control of different control objectives at diverse time scales. The primary control is based on the direct stability, the secondary control on the restoration of the system variables and the tertiary control is found on the optimisation of the economic performance. These control principles are hierarchical and need to have an idea on how such principles can be applied to integrate micro grids into the modern power systems (Feng et al., 2017).

Digital tools have augmented the complexity of power systems and are currently being used to enhance monitoring and analysis, and decision-making. Digital twins are computerized imitations of the physical power system features that are coordinated with actual information in order to enable the proactive study and optimisation of a system. The good thing about digital twins is that they are able to integrate two methods: physical models and data-driven methods to learn about behaviour of a system under various operating conditions. Digital twins are applied in power generation and distribution systems to assist in asset performance optimisation, fault diagnostics and monitoring health. They can only be effective in case of proper modelling of the system, good communication arrangement and strong cybersecurity. The digital twins are becoming increasingly relevant in ensuring the reliability of operations within the context of the growing integration between power systems and tightly coupled cyber-physical systems (Jain et al., 2019).

Power system resilience can be deciphered as the capability of the power system to endure, adjust, and recuperate against acts of disruption like weather extremes, cyberattacks, or mechanical breakdowns. Conventional measures of reliability cannot be used to obtain the adaptive and dynamic nature of resilience in contemporary systems. New strategies that will include real-time data, smart control and adaptive decision-making are therefore needed. The methods of artificial intelligence are being used more and more to improve the resilience of the systems through fast fault diagnosis, predictive maintenance and adaptive control interventions. These methods combine large quantities of operational data to build situational consciousness and make decisions in the face of uncertainty. The conceptual view of the criticality of intelligence and adaptability helps to develop a robust next-generation power system (Mohamed et al., 2019).

3. Power Generation: Principles and Recent Developments

The process of converting primary sources of energy into electrical energy that can be transmitted and distributed is known as electric power generation. Traditional generation systems have been built on thermal, hydro, or nuclear-based prime movers which power synchronous generators. Such generators automatically offer inertia, support voltage and short-circuit current which in the past have guaranteed stable grid operations. These inherent characteristics were employed in the design of traditional power systems, which could be controlled and offered some protection schemes with relative simplicity. Nevertheless, the basic principles of power generation are undergoing redefinition because of the fast shift to renewable sources of energy. Generation systems in modern generation systems are becoming more dependent on power electronic interfaces as opposed to direct electromechanical interfaces, which has radically changed the dynamic of the grid. Consequently, power generation is no longer to be looked at in isolation, but rather be looked into in a close relationship with control, protection as well as market mechanisms.

Solar photovoltaics and wind turbines are renewable energy sources that have become the leading sources of new generation in the world. These sources are variable in nature and are linked to the grid with the help of power electronic converters that decouple the mechanical dynamics of the energy source and those of the electrical grid. Although this decoupling allows the natural inertia that is traditionally given by the synchronous machines to be removed, it also allows the flexibility of control. The converter-based generation presents the issue of frequency stability, voltage regulation and fault ride-through capacity. High-renewable systems do not need advanced control strategies to remain stable in operation, though. This change is a radical change in contrast to the passive nature of the previous generations of inverter technologies and the concept of generation has to be reconsidered.

Inverters that form grids have recently become an important technology that allows stable operation in low-inertia power systems. In contrast to the grid-following inverters, which are based on the external voltage reference, grid-forming inverters perform independent determination of the voltage and frequency reference. Such an ability enables them to simulate the actions of synchronous generators and provide stability to a system. One of the most promising techniques of control is virtual oscillator control. It allows the decentralised synchronisation of the system without the use of phase-locked loops, which enhances stability in weak-grid conditions. Through modelling the dynamics of nonlinear oscillators, virtual inverters using virtual oscillators control, and are able to respond quickly to transient conditions with strong synchronisation in a broad operating space. The features of them render them especially appropriate in the generation systems that are based on renewables (Yap et al., 2019). Figure 2 presents the classification of power generation technologies, highlighting conventional, renewable, and inverter-based systems.

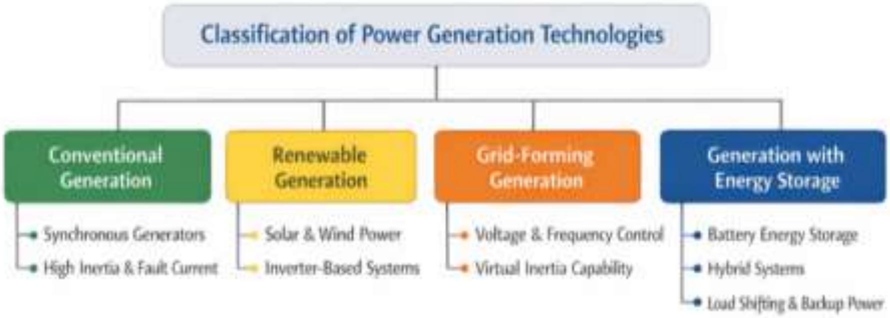

Figure 2. Classification of Power Generation Technologies

Storage of energy has become a basis in the modern power generation frameworks. They are also flexible since they do not tie energy generation and consumption, thus alleviating the unpredictability of renewable generation. Some of the common uses of the battery energy storage system include frequency regulation, peak shaving, ramp-rate control and energy arbitrage. Economic feasibility of energy storage is based on the application-specific cost-benefit analyses as well as market structures. Storage systems may be involved in many value chains such as ancillary services and capacity markets making them financially more attractive. It is also important to understand the operational and economic functions of storage so that they can be effectively integrated into the generation planning and operation (Sidhu et al., 2018).

The generation systems in the market are becoming more and more connected to flexible demand and operate on market principles. Demand response programs enable consumers to manage the use of electricity in response to the messages by price, which is comparable to a virtual generation resource. Distributed pricing policies allow instantaneous coordination between the availability of generation and consumption behaviour. Online pricing systems help in the efficient functioning of the system by motivating load changes during the times when the generation is highly volatile. These plans decrease the expenditure on the expensive generation of reserves and enhance the efficiency of the systems in general. Demand response increases flexibility and operational stress reduction, specifically in highly renewable penetrated systems, from a generation perspective (Li et al., 2017).

Distributed generation has become an integral part of the distribution level, which makes network reconfiguration a more significant generation-supporting mechanism. Operators can minimise the losses and improve the voltage profiles by changing network topology and can also support increased levels of local generation. Feasibility-preserving optimisation methods are such that reconfiguration solutions are not only operational constraint silent, but they can also improve overall system performance. Evolutionary optimisation techniques have been shown to deal with reconfiguration problems, which are nonlinear and combinatorially difficult. Such techniques help to make the integration of distributed generation reliable through adaptation of the network structures to fluctuations in generation patterns (Landeros et al., 2019; Mishra et al., 2017).

The development of generation technologies has great implications for system protection. The converter-based generation adds insignificant fault current to the conventional overcurrent protection scheme, making it less effective. This difficulty is especially acute in high-voltage direct current systems, in which the dynamics of the faults are essentially different from those in AC systems. Protection schemes based on travelling waves have been suggested to counteract the rapid fault propagation nature of direct current ultra-high voltage transmission lines. Such schemes facilitate quick fault identification and isolation, which is important in securing generation assets linked by HVDC links. A basic need to enhance the safety of advanced generation technologies integration is reliable protection (Kong et al., 2016). Table 1 compares different power generation technologies in terms of characteristics, advantages, and associated challenges.

Table 1. Comparison of Power Generation Technologies

Generation Type	Key Characteristics	Advantages	Challenges	Reference
Conventional synchronous generation	Direct electromechanical coupling, inherent inertia	High fault current, stable frequency response	High emissions, low flexibility	Sidhu et al. 2018
Renewable inverter-based generation	Power electronic interfacing, low inertia	Low emissions, scalable deployment	Stability and protection challenges	Dehghan et al. 2015
Grid-forming inverter-based generation	Autonomous voltage and frequency control	Improved stability in weak grids	Control complexity	Yap et al. 2019
Generation with energy storage	Decouples generation and consumption	Flexibility, frequency support	High capital cost	Sidhu et al. 2018

4. Power Transmission Systems

The transmission systems used in the electric power networks are known as the power transmission systems, which facilitate the bulk transmission of power over long distances between the electricity sources and the distribution systems. Historically, transmission networks used to be designed to tie large, centralised power plants with load centres with alternating current technology at higher voltages. This architecture was based on reliability, redundancy and deterministic behaviour with predictable loading conditions. With the swift rise in renewable energy generation in modern power systems, the transmission networks have become much more important as a result of most of this generation being geographically separated from demand centres. Systems need to be able to transfer power over long distances, be able to incorporate variable generation and ensure that the system can continue to operate even in more dynamic conditions. These demands have made transmission networks highly built and managed infrastructures.

High-voltage alternating current transmission continues to be popular because of its ability to work with existing infrastructure and its ability to be converted into different voltages. Nevertheless, HVAC transmission has weaknesses associated with reactive power compensation, stability margins and power losses and especially for long-distance or submarine transmission. To address these limitations, high-voltage direct current transmission has become very popular in contemporary power systems. HVDC transmission has the benefits of reduced losses on long distances, assurance of power flow control, and stability of the system. The rising use of HVDC systems based on the voltage source converters has allowed the interconnection of the asynchronous grids and offshore renewable resources flexibly. With the growth of HVDC networks, it has become a crucial technical issue to be able to provide quick and reliable fault protection (Liu et al., 2018).

The HVDC transmission system is fundamentally a different system in protecting AC systems since there are no natural carriers of zero current, and the fault current rapidly increases. The traditional means of protection applied in the AC networks are not always applicable in the DC world, making it necessary to develop unique fault detection and isolation procedures. Protection DC fault protection solutions encompass converter-based solutions, DC circuit breakers, as well as hybrid protection systems that encompass the combination of mechanical and semiconductor technologies. The choice of pertinent protection strategies is conditional on the topology of the system, converter technology, and the demands on the performance. The safe and dependable functioning of HVDC transmission systems in renewable-intensive power systems requires a comprehensive knowledge of DC fault behaviour (Liu et al., 2018).

The growing adoption of converter-based resources has had a great impact on transmission system control strategies. The use of grid-forming converters is becoming popular due to their capacity to provide voltage and frequency reference points to improve the stability of the system under weak-grid operation. As compared to the conventional grid-following converters, grid-forming units become actively involved in the system regulation and act towards dynamic performance. It has been demonstrated by pilot projects and large-scale demonstrations that grid-forming converters can enhance transient stability, facilitate black-start capability, and enhance resilience in transmission systems with high renewable penetration. The progress shows the increased significance of complex converter control methods on the transmission level (Dehghan et al., 2015). Figure 3 depicts the interaction between transmission and distribution systems incorporating HVDC links and microgrids.

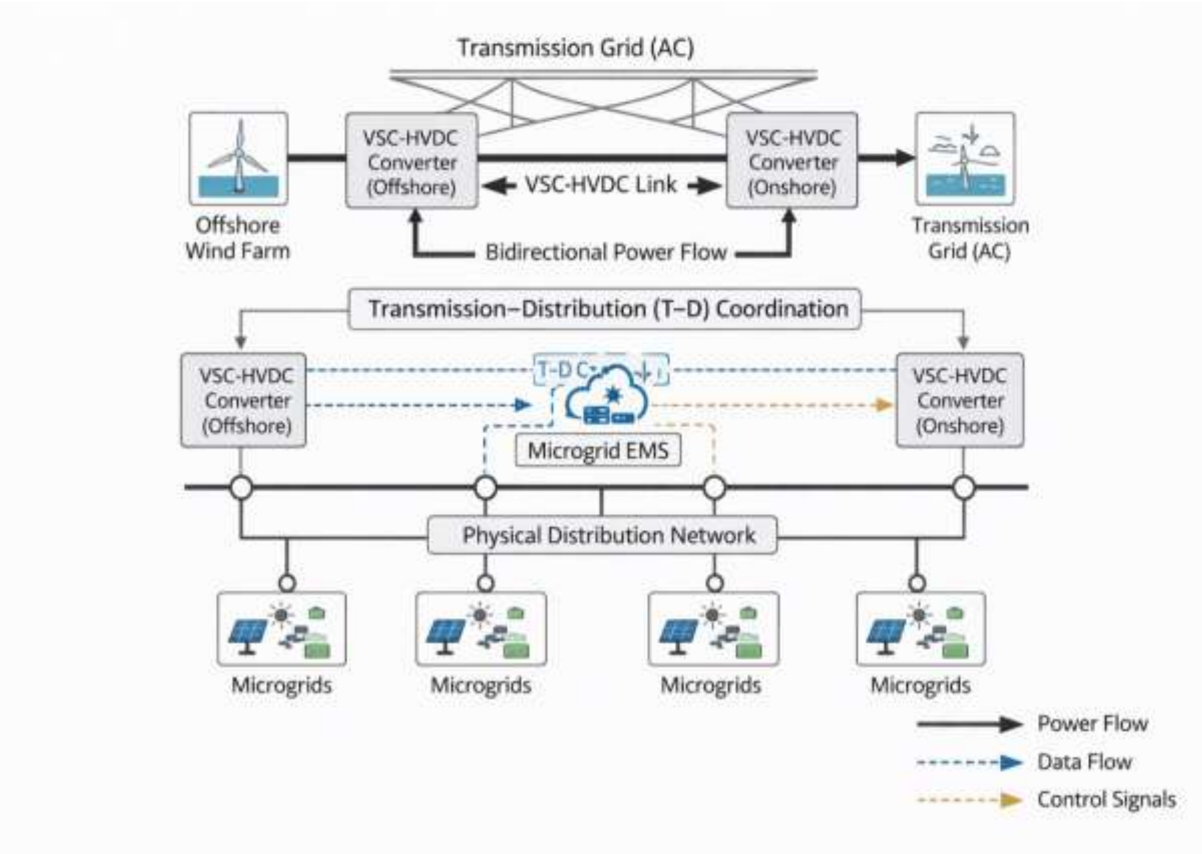

Figure 3. Transmission and Distribution Interaction with HVDC and Microgrids

The active distribution networks are slowly becoming more interconnected with modern transmission systems which contain distributed generation, energy storage, and flexible loads. This engagement breaks the conventional views of one-way power flow and requires more collaboration between the operators of transmission and distribution systems. The reconfiguration of the distribution system is significant in supporting the targets of transmission levels by eliminating congestion, minimising losses, and enhancing voltage profiles. Outlive categorisation of reconfiguration plans underscores their capability to increase the performance of the entire system once coordinated at the network layers (Tao et al., 2018).

Digitalisation has emerged as one of the facilitators of the complex operation of transmission systems. Sensors, communication networks and data analytics enable operators to observe the situation in the system in real time and react proactively to disruptions. Digital twin technology creates a virtual version of the transmission assets which can be used to analyse the scenarios, predictive maintenance and optimisation of operations. Digital twins facilitate the incorporation of variable generation in systems of renewable energy, enhancing the quality of forecasting and the awareness of the systems. They can be used at the transmission level, which will increase the quality of decision-making and facilitate the shift to more adaptive and resilient power systems (Rana & Li, 2015).

In addition to real-time monitoring, digital twins are finding use in planning transmission and developing systems. Digital twins can be used to predict the effects of the new transmission lines, converter stations, and protection schemes by simulating physical behaviour in various operating conditions, and this can be done before actual physical implementation. Digital twins are potentially important, but their implementation is currently challenged by model accuracy, data availability and cybersecurity. These issues must be resolved to make the digital twin-based transmission applications reliable and trustworthy (Tayyebi et al., 2018). Microgrids linked by transmission and hybrid AC/DC networks make systems more complicated to control and estimate. It is necessary to use high-order estimation methods and to control power flows and stability between interconnected systems. Smart microgrid control research indicates that hierarchical and distributed methods are significant in dealing with complexity at the transmission distribution interface (Li & Xu, 2018). Table 2 summarizes major transmission technologies along with their protection requirements and key issues.

Table 2. Transmission Technologies and Protection Requirements

Transmission Technology	Typical Application	Protection Characteristics	Key Issues	Reference
HVAC transmission	Regional bulk power transfer	Mature overcurrent protection	Reactive power limits	Tao et al. 2018
Point-to-point HVDC	Long-distance power transfer	Fast DC fault isolation is required	High protection cost	Liu et al. 2018
Multi-terminal HVDC	Offshore wind integration	Advanced DC breakers and algorithms	Protection coordination	Papadimitriou et al. 2015
Hybrid AC/DC grids	Interconnected systems	Coordinated AC/DC protection	Complexity in fault analysis	Bajwa et al. 2019

5. Power Distribution Systems

The last phase of electricity delivery is power distribution systems, which link bulk power transmission systems with end users. Traditionally, the distribution networks were built as passive radial systems where the power flow was in both directions, that is, from the substations to the consumers. This school of thought emphasised simplicity, reliability and economy in predictable loads. Nevertheless, the distribution of renewable energy sources has been introduced rather quickly, which has considerably changed the nature of distribution networks. The contemporary distribution systems are now being demanded to support bi-directional power flows, variable generation and varied load profiles. These changes have indicated inefficiency of the traditional methodologies of planning and operations that need to be restructured with the introduction of the innovative techniques of control, protection and automation. The rearrangement of the distribution systems to accommodate the high renewable penetration has now been taken to be a major problem in the achievement of sustainable power systems.

The move to the incorporation of renewable sources of energy at the level of distribution level creates both technical and operational problems. When not managed, distributed generation may cause voltage rise, thermal overloading, as well as miscoordination of the protective equipment. Moreover, one can also note that the stochasticity of renewable generation also makes system functioning and planning more uncertain. Voltage regulation, network strengthening and enhanced inverter features are some of the grid adaptation measures that have been suggested to counter such problems. The integration of renewables at the distribution level will need coordinated planning that will consider both the technical constraints and the long-term sustainability goals. An international view of grid adaptation emphasises the need to align regulation and invest in smart infrastructure in distribution (Bello et al., 2015).

The methods of planning distribution systems have always been dedicated to deterministic load growth and reliability requirements. Nevertheless, growing uncertainty over renewable generation and changing demands trends require more advanced methods of planning. Planning frameworks that are reliability constrained can include probabilistic projections of loads and generation to guarantee limited system operation under various operating conditions. Though these practices typically work at the transmission level, the principles can also be applied to the distribution networks at high renewable penetration. The introduction of reliability limitations into the planning processes helps distribution systems to sustain reasonable service levels without affecting the variable energy sources (Le Blond et al., 2016).

The active distribution networks formed by the transformation of passive distribution networks have made the functioning of the systems more complex. Distribution networks entail real-time monitoring, adaptive control and intelligent decision making to facilitate the management of resources that are distributed. To realise these needs, there is a growing use of artificial intelligence methods to support high-order prediction, optimisation and fault detection. AI-based techniques contribute to the functioning of the distribution system, namely, to the accuracy of the load and generation forecast, reconfiguration optimisation, and better protection coordination. The capabilities are especially useful within environments that are highly variable and not very observable. Artificial intelligence applications have thus emerged as a major facilitator of effective and dependable operation of distribution systems (Mariam et al., 2016).

Distributed generation, power electronic interfaces and complex network topologies have made protection of distribution systems an even more difficult challenge. Traditional overcurrent protection systems might not be able to isolate or sense faults in conditions of bidirectional flow of power. These issues are also complicated in those systems that are connected with multi-terminal HVDC networks or hybrid AC/DC systems. To provide advanced protection, adaptive settings, communication-based schemes, and rapid fault detection algorithms have been used to achieve system safety. Experiences of protection methods made to multi-terminal HVDC grids can be relied on to inform future power distribution-level protection methods (Bajwa et al., 2019).

One of the architectural solutions to the enhancement of the flexibility and resilience of the distribution system is microgrids. Microgrids can run alone or together with the main grid and this is done through the addition of distributed generation, energy storage and controllable loads in a local system. The stability is increased with the capacity during the periods of unrest and making good use of the available energy sources. Despite the benefits, there are certain challenges associated with microgrids such as coordination of control, protection and interoperability. Architectural diversity, as well as the discrepancy in the purpose of operation complicate system design and integration. In order to get over these challenges, there must be the existence of standardised control systems, and robust protection mechanisms to meet distribution level applications (Beheshtaein et al., 2015).

Resilience is a new performance characteristic of the contemporary distribution system because of the increasing extreme weather events and cyber-physical threats. Resilience as opposed to the traditional standards of reliability is concerned with the capacity of the system to buffer, adapt to new conditions, and recover soon after the disruptions. The overall grid resilience is achieved through distribution systems since they are in direct contact with the consumers and distributed resources. Distribution system resilience process encompasses hardening of infrastructures, flexibility in operation, and intelligent control. The measurement of system performance and investor choices is based on quantitative resilience indicators (Kaivo-oja et al., 2019). Table 3 outlines various distribution system architectures and their corresponding control strategies and benefits.

Table 3. Distribution System Architectures and Control Approaches

Distribution Architecture	Description	Control Strategy	Benefits	Reference
Passive radial distribution	Unidirectional power flow	Centralised voltage control	Simplicity, low cost	Bello et al. 2015
Active distribution network	Bidirectional power flow	AI-assisted adaptive control	Improved efficiency	Mariam et al. 2016
Grid-connected microgrid	Operates with main grid	Hierarchical control	Enhanced flexibility	Beheshtaein et al. 2015
Islanded microgrid	Autonomous operation	Localized control	Improved resilience	Nurmanova et al. 2019

6. Digitalization and Intelligence in Power Systems

The evolution of the electric power system is so rapid that it has been followed by the digital technologies changing accordingly. The most critical enabling factor of the contemporary functioning of the power systems has been the digitalisation as it has allowed the advanced monitoring, control and optimisation of all layers of the power system: the generation, transmission and distribution layers. The detecting mechanisms with the help of the communication systems and computational intelligence have enabled the transition to the rule-based functionality that worked in a stagnant mode to the adaptive and data-oriented operation of the system. Real-time data acquisition, self-directed decision-making, and enhanced situational awareness are the characteristics of the digitalised power systems. These must be able to deal with the uncertainty of the renewable generation and to organize the distributed energy resources, and assure the stability of the system in an ever more complex operating environment.

The artificial intelligence has proved to be a formidable instrument to counter the complexity and uncertainty of the current power systems. The AI techniques are usually applied in predictions, optimisation and management procedures which cannot be easily solved using the conventional analytical tools. Machine learning algorithms enable systems to adjust to new operating conditions and learn by the history without modelling the dynamics of the system in any manner. The AI applications to the management of power systems are load prediction, fault detection and dynamic security testing. These applications are useful in making the operations within the system more efficient and better responding to disturbances by the system operators. The increased application of AI is a sign of a general tendency to intelligent, autonomous control of power systems.

A key application of intelligence in power systems is demand response so that loads that can be adjusted flexibly can play an active role in the operations of the power system. Smart load control policy utilises real-time to good effect and optimisation algorithms to adjust consumption trends to suit the requirements of the system. This flexibility is quite useful, in particular, in highly-renewed systems, where the variability of supply must be dynamically balanced. Reinforcement learning has been used to apply residential demand response since it enables thermostatically controlled loads to set consumption based on the system conditions and user preferences. These solutions demonstrate how an AI-based load control can provide quality flexibility with no harm to the consumers (Ruelens et al., 2016).

The digital twin technology has gained much attention as a technology of linking physical power system resources to the virtual resources. A digital twin refers to a model of a physical device that is data-synchronised in real-time such that, one can forecast, optimise the performance of the device and measure the risk. Applications Digital twins in power systems Digital twins aid in asset health monitoring, predicting faults, and operational planning applications. Digital twins combined with artificial intelligence are more analytical because they can be refined using data and make adaptive decisions. Such synergy enables the digital twins to develop with the physical systems enhancing precision and relevance as time goes by. The synthesis of AI and digital twins is one of the promising directions in the innovation of the future power system (Elkhatib et al., 2018). Figure 4 shows the digitalization and intelligence framework applied across modern power systems.

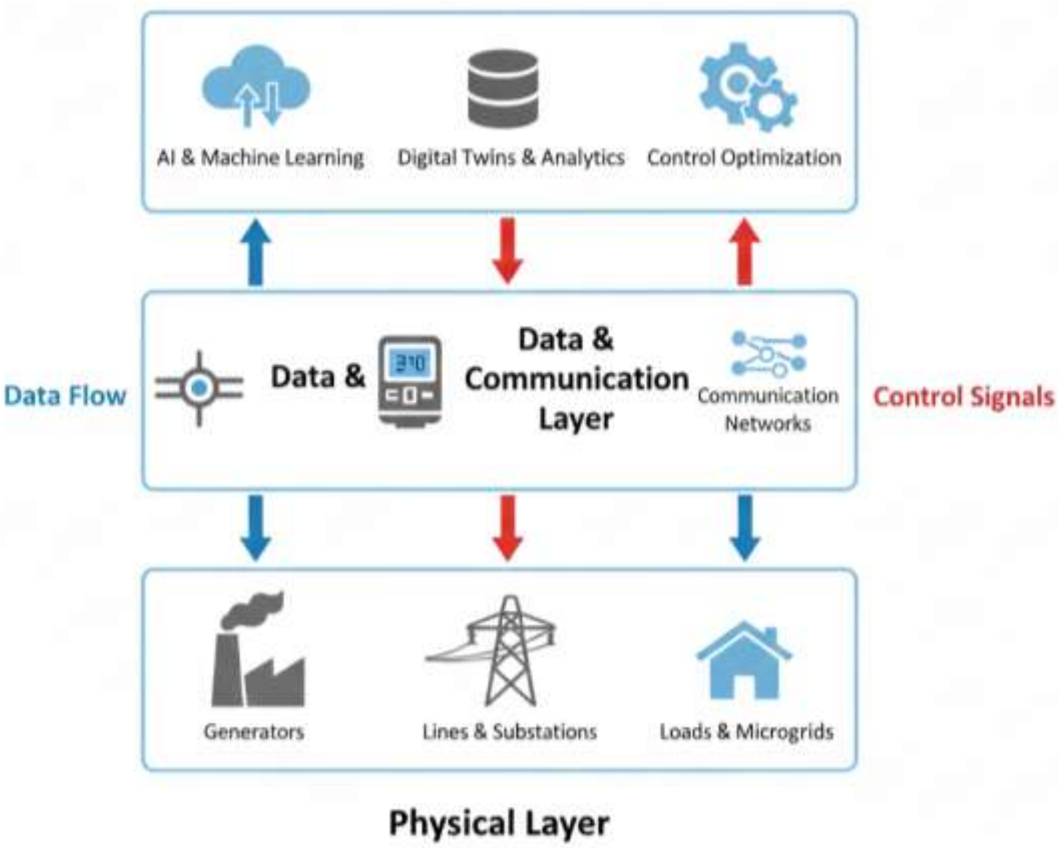

Figure 4. Digitalization and Intelligence Framework for Power Systems

According to digitalisation and intelligence in the field of power systems, microgrids can be listed among the most prominent beneficiaries. They need to be operated in a coordinated manner involving distributed generation, energy storage and loads under grid-connected and islanded conditions. Microgrids can have intelligent control strategies which allow them to be stable, performance-optimised optimum and highly responsive to disturbances. The use of hierarchical and distributed control architectures is of relevance, as demonstrated by comprehensive surveys of microgrid control. These architectures take advantage of local intelligence in order to handle rapid dynamics and coordinate more global goals like in economic optimisation and energy management. Management of the complexity of the microgrid functioning requires digital tools and smart algorithms (Sen & Kumar, 2018).

Converter pivot grids are an important component that allows digitalised power systems to operate in a stable mode with significant inverter-based resources penetration. These converters define power levels and frequency standards, which they can use to help provide stability in the system when on weak grids. The grid-forming converters have advanced control algorithms that provide the converters with the capability to synchronise with the grid and share loads. Studies on grid-forming control methods point to the need to have strong synchronisation schemes and adaptive control methods. The intelligent control is used to make converters more responsive to disturbances and coordinate the action of multiple units. Future intelligent power systems rely on grid-forming converters, hence (Beheshtaein et al., 2015).

The power system has some serious implications regarding digitalisation and intelligence. Conventional protection systems usually do not work well in settings where there is a high density of inverter-based resources and complicated network structures. The intelligent protection strategies have real-time measurements, adaptive settings, as well as communication-aided coordination to enhance fault detection and isolation. There is an acute problem of protection in microgrids because of changing fault current values and changing operating conditions. Comparative microgrid protection

structures demonstrate the necessity of smart and adaptable schemes capable of changing in response to any environmental changes and providing a stable functioning (Moon et al., 2019).
On top of converter control on an individual converter basis, grid-forming inverters are becoming more and more significant at a system level. They enhance the frequency control, voltage stability and black-start of systems where the renewable energy prevails. Surveys of grid-forming inverter applications also focus on the fact that they will eventually be used to substitute traditional synchronous generators in the power system. It takes system-level coordination of grid-forming inverters with coordinated control strategies and standardised inverter interfaces. This coordination is provided by intelligent algorithms that allow adapting their parameters and cooperate with distributed resources (Pan et al., 2019). Table 4 highlights key digitalization and intelligence techniques used in power systems and their application areas.

Table 4. Digitalization and Intelligence Techniques in Power Systems

Technology	Application Area	Function	Key Benefit	Reference
Artificial intelligence	Operation and planning	Forecasting and optimisation	Improved decision-making	Mariam et al., 2016
Digital twins	Generation and grids	Real-time system replication	Predictive maintenance	Elkhatib et al., 2018
Reinforcement learning	Demand response	Adaptive load control	Enhanced flexibility	Ruelens et al. (2016)
Grid-forming converter control	System operation	Voltage and frequency support	Stability enhancement	Beheshtaein et al., 2015

7. Power System Resilience and Reliability

Power system resilience is the capability of an electric power system to absorb, adjust to, and quickly recover from a disruption without the degradation of acceptable quantities of service. Resilience is the opposite of traditional reliability, which is mostly concerned with the likelihood of component failures and anticipated outage times. Resilience is concerned with system performance during events of high impact and low probability. These events are extreme weather conditions, cyber attacks, equipment, and operational uncertainties relating to high renewable energy penetration. The increased complexity of contemporary power systems has revealed the shortcomings of traditional reliability measurements and approaches to power system planning. With the transformation of power systems to interrelated cyber-physical systems, resilience has become the primary design and operational goal. Achievement of resilience demands synergistic plans regarding the generation, transmission, distribution, and demand sides of resources.
Examples that affect resilience at the generation level include the variety of energy sources, the capacity of the generation assets to be flexible and the capacity to have fast-reacting control mechanisms. The sources of renewable energy present variability and uncertainty and may pose a challenge to the stability of the system as long as it is not well managed. Inverter-based generation control strategies have thus been developed to be at the forefront in improving resilience. The grid-forming converter control techniques allow resources that are based on inverters to actively contribute to regulating voltages and frequencies during disturbances. These converters enhance the robustness of a system in the case of a high level of renewable penetration by offering a high response time and self-contained work. Extensive surveys of grid-forming methods of control stress the critical role that they perform in ensuring stable operation of resilient power systems (Parhizi et al., 2015).
Networks used in transmission and distribution are a core part of the apparent phrase of whole system resilience. The network topology, redundancy, and controllability affect the isolation capability of the system in case of faults and rerouting power. Lax network arrangements and high control measures contribute to the ability of power systems to respond to variations in conditions. The grid-forming converters also help achieve network-level resilience by providing stability in weak grids or partially disconnected grids. To determine the effects of converter dynamics on system resilience, modelling

and control studies indicate the critical role of properly modelling converter dynamics. Strong converter models facilitate the development of control strategies that can help to increase the level of network stability and recovery (Lin et al., 2018).

Load-side flexibility is becoming accepted as one of the major power system resilience contributors. Demand response programs enable consumers to respond electrically to the condition of the system, and they prove to be a useful resource to counteract demand and supply during a disruption. Distributed demand response schemes create resilience due to a decrease in reliance on centralised control and localised adaptation. Population game theory is a resilient demand response frameworks that allow large groups of consumers to take part in the functioning of the system without global coordination. These methods enhance the robustness of systems by depending on decentralised decision-making and on-time response to disturbances (Srikantha & Kundur, 2016).

Decentralised control and optimisation methods are very important in increasing resilience in the current power systems. The centralised control systems can easily be compromised through a breakdown of communication or a cyberattack, but the decentralised systems, by default, have a high tolerance as they decentralise decision-making among components of the system. Power system operation has been applied to consensus-based optimisation methods to allow the coordinated decision-making process to be implemented without the use of a central controller. Demand response coupled with completely decentralised strategies on optimal power flow enhances resilience by ensuring the functionality of the system even in the cases of partial communication failures (Wang et al., 2016).

The microgrids are generally considered as the major facilitators of power system resiliency as they can go independent in the case of grid disruptions. Microgrids can supply power to critical loads when the main power is present, as they incorporate local generation and energy storage and controllable loads. They can island, which makes the systems more robust and minimises the effect of large-scale failures. The increasing number of works devoted to resiliency-oriented design and functioning marked the development of the study of microgrid control. Controllable architectures are created so that they allow the swap of grid-connected and islanded status to accelerate system recovery and flexibility (Nurmanova et al., 2019).

Without elaborate frameworks, which consider the interactions between the generation and network components, and load components, power system resilience cannot be measured. Systematic reviews underline the importance of multi-dimensional indicators of resilience where the time-dependent performance, recovery velocity, and resilience are taken into consideration. These measures also enable the making of good decisions and plans to invest in an attempt to enhance the strength of the systems. The inter-relationship between the technical, operational and organisational variables is the focus of the holistic approach to resilience. Such dependencies will aid us to learn how to develop effective resilience-strengthening plans (Arghandeh et al., 2016).

8. Regulatory Frameworks and Grid Codes

Codes and regulatory systems are essential in ensuring that the running of electric power systems is safe, stable and effective. As the power systems with large shares of renewable energy and inverter based resources and digitalised operation come into play, the old regulations introduced in centralised, synchronous generation become less and less applicable. New grid codes are then supposed to be made in line with new technical realities without compromising the stability of the systems and also equity in the electricity markets. Regulation is a link between the technological innovation and system coordination. The grid codes are properly constructed and dictate the lowest technical demands of grid connection, operating behaviour and protection performance such that the different system components can operate in cooperation with each other. Without an appropriate regulation being modified this means that technological innovations will lead to a disjointed solution and an increased risk of operation.

The converter-interfaced generation is growing at a very rapid rate, which has radically changed the grid dynamics, and grid connection necessities must also be revised. Classical grid codes gave much attention to synchronous generators with the main emphasis on such parameters as inertia contribution and short-circuit current. By comparison, more recent grid codes are also setting functional requirements on inverter-based resources, such as fault ride-through support, voltage sponsoring, and frequency response. HVDC systems based on modular multilevel converters are especially sensitive to the advanced protection requirements. Compared to the AC systems, fault behaviour in DC networks is much different and, therefore, specialised protection algorithms and quick response mechanisms are needed. In-depth literature regarding DC fault protection points out the importance of standardised performance requirements that enable interoperability and reliability of the systems (Papadimitriou et al., 2015).

The current power systems represent cyber-physical systems, which are a combination of physical infrastructure, communication networks, control software, and data analytics. This integration gives rise to new vulnerabilities going further than any conventional electrical failure to cyber threats and communication breaks. The regulatory systems should hence take care of the physical and cyber aspects of system resilience. Cyber-physical resilience demands communicative coordinated standards involving reliability, integrity of data and recovery of the system. The regulations that consider cyber-physical perspectives help the utilities and system operators to address the interdependencies in a more effective manner. An overall overview of cyber-physical resilience helps to underline the need to have a holistic view of regulations that consider the interplay between physical and digital systems (Panteli et al., 2017).

Microgrids pose special regulatory challenges because they can be connected to the grid as well as function in an islanded mode. The current grid codes usually do not include explicit functions on how microgrids should operate and thus there is confusion on the roles of the microgrids, coordination of protection, and the participation of the microgrids on the market. Technical requirements that have to be established to define interconnection, control hierarchies, and switching between operating modes must be effectively regulated. Microgrids have highly hierarchical control structures that are used to deal with the various time scales and control targets. A strategic fit of regulations to the hierarchical control concept also permits the safe operation of microgrids, which would be in line with the overall system functionality. Hierarchical control reviews of constructing microgrids indicate that regulatory frameworks should be established to be aware of multi-layer control architectures and their operational implications.

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The shift to low-carbon power systems creates new regulatory issues connected with long-term planning, coordination of investment and system flexibility. The use of traditional methods of planning that are deterministic-based is becoming less and less satisfactory due to renewable variability and policy uncertainty. Regulators thus need to assist planning methodologies that embrace uncertainty, flexibility and creativity. Planning tools that are based on artificial intelligence are drawing interest due to their capacity to handle huge amounts of data and to analyse complicated trade-offs. These tools facilitate the planning process based on scenarios and facilitate more informed regulation. The AI-based planning systems can offer useful information to use in adjusting regulatory goals with technological and environmental aims (Vugrin et al., 2017).

There are growing regional and national interconnections in power systems especially with HVDC interconnections, and cross-border electricity markets. The grid codes need to be harmonised to provide interoperability and effective power exchange. Different technical requirements may result in integration barriers and complexity of systems. International coordinators are making efforts to bring the grid code requirements in tandem with the renewable integration, converter behaviour, and the protection performance. Although the full harmonisation might not be easy because of the regional differences, convergence to some shared principles is beneficial in terms of the resilience of the system and its operational effectiveness.

9. Open Challenges and Future Research Directions

9.1 Increasing Penetration of Inverter-Based Resources

The growing use of inverter-based resources is one of the gravest issues of future power systems. With the traditional synchronous generators being increasingly substituted by the green sources of energy, the system becomes deprived of the natural inertia and fault current provision. Such a transition radically changes the dynamics of the system and breaks certain conventional assumptions applied in the process of planning, operation, and protection. The next step in the field of work should be a stable functioning in low-inertia conditions by creating sophisticated grid-forming control designs, standard performance specifications, and scalable coordination protocols. Interactions between large groups of grid-forming inverters have also been an unsolved issue of understanding, especially when operating under stressed conditions, as well as when the system is being restored.

9.2 Protection of Converter-Dominated and Hybrid AC/DC Grids

One of the significant technical constraints in the current power systems is protection. Grids with converters dominate have lower fault current, transient dynamics, and multiple complicated fault signatures that are problematic to standard protection schemes. These problems are also compounded in the hybrid AC/DC networks and multi-terminal HVDC systems. The positive outlooks of future research involve the creation of faster, selective, and adaptable protection schemes that are based on high sensing, communication and signal processing methods. Protection and control, as well as system-wide situational awareness, must be integrated to achieve reliable fault detection and isolation in the network topology of complex systems.

9.3 Scalability and Interoperability of Digital Twins

Digital twins have proven to be promising in improving the power system monitoring, planning, and functioning. Nonetheless, it is highly challenging to scale digital twin solutions on a small-scale asset to a large-scale system application. These are the complexity of the models, the computational cost, data synchronization and cross-platform heterogeneity. The future work will deal with standardized digital twins architectures, interoperability with the current energy management systems, and cybersecurity. Studies are also required to come up with hybrid modeling that integrates both physics-based and data-based models and be transparent and reliable.

9.4 Artificial Intelligence Trustworthiness and Explainability

AI has already become a necessary element in the functioning and design of the modern power systems. Along with many benefits, the use of AI creates transparency, robustness, and trustworthiness concerns. Most AI models are black boxes, which reduces their use in safety-critical applications, e.g., protection and real-time control. Further studies ought to focus on explainable AI methods that can give insights that can be interpreted with regard to decision-making processes. Secondly, stringent validation systems are needed so that AI models can be operational using unknown operating conditions and extreme situations. Several factors that need to be tackled to promote its adoption include data quality, bias, and cybersecurity risks.

9.5 Coordination Between Transmission and Distribution Systems

The growing link of both transmission and distribution systems is in itself a potential opportunity and a challenge. Microgrids, distributed energy resources, and active distribution networks now have an impact on the behavior of a bulk system, necessitating more coordination between historically distinct areas of activity. The future studies should aim at coming up with integrated transmission-distribution coordination models that can facilitate real time information sharing, joint optimization, and control objectives. There should also be the regulation and institutional barriers that should be overcome to facilitate the collaboration of the system operators and other stakeholders.

9.6 Microgrids at Scale and System-Level Integration

Microgrids have been demonstrated to be beneficial in strengthening resilience and local-level flexibility. There are however new challenges associated with scaling the implementation of microgrids and connecting large scale numbers of microgrids to the broader power system. These are multi-microgrid coordination, market participation and system-wide effects of stability. Further studies are needed in the future on multi-microgrid coordination schemes, standardized control interfaces, and market schemes, which can encourage the microgrids to offer ancillary services. The emergent behavior as a consequence of the large-scale implementation of microgrids is important to understand in order to achieve the stability of the systems.

9.7 Resilience-Oriented Planning and Operation

Although much attention has been given to resilience, the actual implementation has not been well done because there has not been universal measures and planning frameworks. The conventional reliability-driven methods cannot represent system behavior in extreme and compound disturbances. Future studies ought to be on creation of resilience-based planning tools, which will integrate uncertainty, flexibility, and recovery processes. A combination of resilience measurements in investment decisions and operations will be critical in equipping power systems with climate change and other emerging threats.

9.8 Data Availability, Privacy, and Cybersecurity

Contemporary power systems are now dependent on data gathered on the distributed sensors, smart meters and communication networks. On the one hand, the availability of data allows using sophisticated analytics and intelligent control, but on the other hand, it is associated with privacy, ownership, and cybersecurity issues. The research topics that should be considered in the future include secure data-sharing models, privacy-sensitive analytics, and resilient communication models. To ensure that people can trust digitalized power systems, it is essential to ensure the integrity and availability of data.

9.9 Human–Machine Interaction and Workforce Transformation

With the continued automation and increasing intelligence of power systems there is a shift in the role of human operators. The importance of successful human-machine interaction is that it sustains the situational awareness and makes safe decisions in abnormal conditions. The further research should be aimed at the interface design, decision-support tools, and other training techniques to help the operators to effectively operate the intelligent systems. The development of the workforce and skills is also fundamental towards the continuity of system reliability in the long term.

10. Conclusion

In this review, a detailed discussion of power generation, transmission and distribution systems has been provided, focusing on the underlying concepts as well as what has developed over the last few years. The move to renewable energy and inverter-based resources is re-architecturing the traditional power system to bring forth new challenges in terms of stability, protection, planning, and coordination. The development of grid-forming converters, energy storage systems, and flexible demand mechanisms has become some of the most important enabling factors of the reliable functioning in low-inertia and highly dynamic environments. In both the transmission and distribution levels the use of HVDC technologies, active distribution systems and microgrids has increased the flexibility of the system and the complexity of its operations. Digitalization with the help of artificial intelligence and digital twin is becoming an increasingly significant part of making systems smarter and more observable, more controllable, and more decision-making. The tools allow operationalizing data-driven and facilitating resilience-based planning in the face of uncertainty. The increased significance of resilience as a fundamental performance characteristic has also been noted in the review as a fundamental coordinated strategy that needs to be applied at generation, networks, and loads. The regulatory frameworks and grid codes should keep on changing with the emergent technology and to be able to integrate the systems with security. All in all, sustainable, resilient and intelligent power systems will need holistic solutions which will include technological creativity, sophisticated control and adaptive regulatory actions.

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