IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 19 June 2024, accepted 3 July 2024, date of publication 8 July 2024, date of current version 17 July 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3425272

TOPICAL REVIEW

Review of Challenges and Research Opportunities for Control of Transmission Grids

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This work was supported by UT-Battelle, LLC, with the U.S. Department of Energy (DOE), Office of Electricity, Transmission Reliability and Renewable Integration (TRRI), under Contract DE-AC05-00OR22725.

ABSTRACT The integration of various grid-enhancing technologies is crucial for addressing the current challenges faced in controlling transmission grids. The growing variability in energy supply necessitates innovative solutions such as advanced grid monitoring and control systems, energy storage technologies, and flexible grid infrastructure. These technologies are essential for balancing the intermittent nature of renewable energy sources (RESs) and ensuring a stable and reliable electricity supply. This paper offers a comprehensive review of grid-enhancing technologies, incorporating insights from worldwide academic papers and various existing industrial projects that address current challenges and enhance the functionality, reliability, and sustainability of transmission grids. The findings highlight that modernizing grid infrastructure and integrating cutting-edge digital technologies are vital for effectively incorporating a growing number of RESs and enhancing overall grid resilience and efficiency. In addition, the paper explores future opportunities for improving the control of transmission grids, emphasizing the need for continued innovation and investment to meet evolving energy demands and support the transition to a more sustainable energy system.

INDEX TERMS Control theory, efficiency, reliability, resilience, stability, transmission grids.

I. INTRODUCTION

Numerous initiatives from both public and private sectors are underway with the objective of transitioning the United States to economy-wide net-zero greenhouse gas emissions by the year 2050. Technically, the goal of net-zero emissions by 2050 is achievable because the technologies required to reduce carbon emissions in high-emission sectors are currently available or under development [1]. The ability to generate electricity from wind and solar energy will be the primary factor driving the reduction of emissions.

The associate editor coordinating the review of this manuscript and approving it for publication was Cuo Zhang.

"Smart" has become a critical and widely used term to describe an electric power grid that is more efficient, resilient, reliable, and sustainable [2]. The evolution of traditional power grids into "smart grids" represents a significant shift in how electricity generation, transmission, distribution, and consumption are managed and optimized [3]. In the "Smart Transmission Grid" infrastructure, novel materials and devices, advanced power electronics devices, advanced sensing and measurement devices, advanced communication, and advanced control technologies, including machine learning, would be needed to create transmission infrastructures that are not only more efficient and reliable but also more resilient against various challenges such as integration of more renewable energy sources (RESs) and potential disturbances [4].

With the development of technologies in power electronics, computing, communications, and others, the control of transmission grids becomes a complex and critical aspect of modern power systems, ensuring stability, efficiency, and reliability in the delivery of electricity [5], [6]. The architecture of a transmission grid refers to the interconnected network of transmission lines, substations, transformers, and other components that facilitate the high-voltage transfer of electricity from generation plants to distribution networks [4], [7]. Typically, this architecture is characterized by its configuration, such as radial [8], loop [9], or meshed networks [10]. Each configuration provides unique advantages in terms of reliability and efficiency. Central to this architecture is the concept of grid synchronization, which ensures that all connected generators operate in phase and at a consistent frequency [11], [12]. This requirement is critical for grid stability as it prevents power outages and disruptions in the electrical supply [13]. In power systems, control theory is applied to maintain system stability and to respond dynamically to changes in demand and supply. Different control systems are needed for different timescales, such as fast-acting systems for immediate response and slower-acting systems for long-term stability maintenance [7]. Fast-acting systems are required for microsecond and millisecond events, whereas slower-acting systems can handle longer-term changes, as shown in Figure 1. Each control strategy plays a specific role in ensuring the reliability, stability, and efficiency of the power grid. They work together to effectively respond to various events and maintain the balance between electricity generation and consumption.

- Primary Control: This layer of control, also known as frequency control, involves automatic adjustments in power output from generators to maintain the system frequency within acceptable limits. This control is usually achieved via governor action in generators, which respond to deviations in frequency [14]. Primary control operates independently at each generator based on its own frequency measurement and droop setting.
- Secondary Control: This layer of control focuses on the transmission system's voltage/frequency regulation. It involves automatic generation control (AGC) systems, which adjust the power output of generators across the grid to maintain system frequency and power balance [15].
- Tertiary Control: This level involves market mechanisms and economic dispatch. It optimizes the economic efficiency of power generation by adjusting the output of various generators based on market conditions, operational constraints, and economic dispatch models [16].
- Supervisory Control and Data Acquisition (SCADA): SCADA systems provide real-time monitoring and control of the power grid. They can collect data from various points in the system and allow operators to make decisions and control devices remotely [17].
- Wide-Area Monitoring, Protection, and Control (WAMPAC): WAMPAC systems involve monitoring the overall health and stability of the power system, enabling the rapid detection and isolation of faults or disturbances, and the coordination of control actions over a large geographical area [18].
- Forecast: Grid operators must forecast electricity demand and generation over different timescales to ensure adequate resources are available [19], [20].
- Planing: Transmission expansion and generation planning processes involve long-term planning and investment decisions to meet future electricity demand [21], [22].

Frequency stability and control in today's power systems face new challenges arising from the growing integration of power electronics-based renewable energy and loads [23]. The challenges to transmission grid control are mainly caused by the reduction of the system rotational inertia as inverter-based resources (IBRs) gradually replace synchronous generators (SGs) [24], [25]. Reduced rotational inertia in a power system can negatively affect the grid frequency response performance as well as the feasible regulation resources. From the grid control perspective, the emulation of systematic inertia and regulated active power injection from flexible reserve sources are potential solutions. Considering the fast and accurate control characteristics of IBRs, the regulating power can be provided in a short time [26]. In addition, demand response (DR) (i.e., controlling loads and flexible demand-side units) provides a promising solution for power grid frequency regulation [27]. The switching-based controllability of loads enables the demand to respond faster [28] to system disturbances compared with conventional SGs. This ability, together with recent advances in monitoring, computing, and communication technologies, makes demand-side resources ideal candidates for grid frequency control. However, the increased reliance of modern power grids on information technologies and their transformation to complex cyber-physical systems has revealed their vulnerabilities to cyberattacks [29]. Frequency control is one of the most critical functions and is therefore a likely target of attacks [30], [31]. Although rapid progress in information and communication networks offers many advantages in frequency regulation, it increases risks of cyber intrusion and attacks, causing reliability issues.

Nowadays, there exist various review articles that summarize the technologies in transmission grids. Article [32] offers a global perspective combined with a detailed technical and market analysis, which is only focused on high-voltage direct current (HVDC) transmission technologies. In [33], Numan et al. summarized the academic and practical understanding of how optimal transmission switching can be used to enhance the flexibility and efficiency of electrical power grids. Paper [34] provides an in-depth review of the latest developments in sensor technologies used in transmission and distribution grids. In [35], the optimization methods for improving the resilience of power systems through

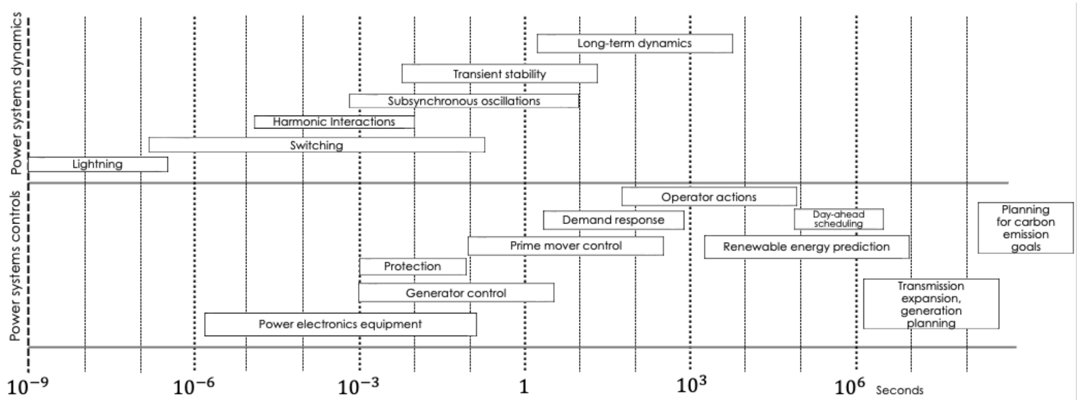

FIGURE 1. **Timescale of power system dynamics and controls.**

transmission network reconfiguration are summarized. Paper [36] offers a comprehensive review and new insights into power system stability amid the rising use of RESs and power electronic devices. In [37], it is summarized how high PV penetration affects various aspects of power systems, including voltage levels, frequency, protection systems, harmonics, rotor angle stability, and flexibility requirements. Furthermore, there exist various review papers that provide state-of-the-art methods used in smart grids, such as economic load dispatch methods [16], WAMPAC systems [18], virtual inertia solutions [38], voltage control methods [39], etc. When compared with existing review articles, the key contributions of this paper are outlined as follows:

- Provided a broader review of various grid-enhancing technologies, offering a comprehensive view that connects technical and market perspectives into a coherent whole.
- Carried out a thorough analysis of the current challenges faced in controlling transmission grids, such as integrating RESs, ensuring stability amidst growing variability, and cybersecurity threats, etc.
- Analyzed the latest advancements in technology that address these challenges, such as advancements in modeling methods, real-time monitoring and control systems, AI for grid management, etc.
- Reviewed the existing industrial projects that address current challenges and enhance the functionality, reliability, and sustainability of transmission grids. In addition, growing opportunities for improving transmission grids are given.

In line with the above contributions, the paper is organized as follows: First, the architecture of the transmission grid is introduced by discussing the essential components of smart grids in Section II. Those will be the main assets involved in the control system of the transmission grid. Then, Section III discusses the critical challenges of grid control, including issues such as voltage regulation, frequency control, grid stability, grid resilience, and interoperability. It explores the complexities of maintaining stability and reliability in the grid, especially as RESs become more prevalent. This section delves into the various obstacles and difficulties faced in maintaining and managing the stability and reliability of the grid. Section IV provides a comprehensive summary of the most recent advancements in grid control technologies. This includes an in-depth analysis on essential grid control components, the modeling methods of the grid and its assets, as well as cutting-edge control methods designed for transmission grids. Additionally, this section delves into the practical implementations of these state-of-the-art control techniques, offering valuable insights into their real-world applications and benefits. Lastly, Section V provides an overview of current industrial practices in grid control, including the technologies and methods used in the industry today. It also discusses future opportunities for advancements in grid control, such as the integration of RESs, smart grid technologies, and advanced control systems.

II. GRID ARCHITECTURE

The transmission grid, as a backbone of the electricity supply system, comprises several key components (shown in Figure 2) that work together to facilitate an efficient transfer of high-voltage electricity from generation plants to distribution networks.

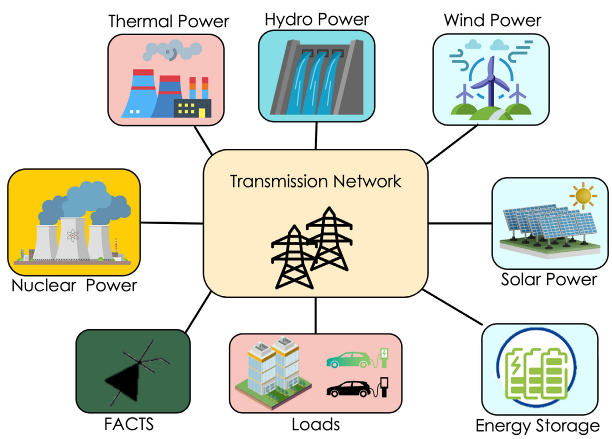

FIGURE 2. **Transmission networks.**

A. TRANSMISSION LINES

Transmission lines can carry either alternating current (AC) or direct current (DC) [40]. The high-voltage drop occurs across the AC terminal lines when their end terminal voltages are equal. The DC transmission line is free from inductance; therefore, no voltage drop occurs across the line. At the same voltage level, the DC transmission line has less stress than the AC transmission line because it has less insulation than the AC line [41]. In general, the AC lines face synchronization and stability issues, whereas the DC transmission line is free from these problems [42].

B. FOSSIL FUEL POWER PLANTS

Fossil fuel power plants, including coal, natural gas, and oil-powered stations, are traditional sources of electricity. They use fossil fuels to generate steam, which then drives turbines connected to generators. Until 2023, fossil fuel power plants provided most of the electrical energy used in the world [43]. However, they are major emitters of carbon dioxide, a greenhouse gas that is a major contributor to global warming, and the control of emissions from fossil fuel power plants is a complex issue [44].

C. NUCLEAR POWER PLANTS

Utilizing nuclear fission to generate heat, nuclear power plants produce steam to drive turbines connected to generators [45]. Despite concerns over waste and safety, nuclear power is a significant source of base-load power in many regions. Considering the climate change and the carbon dioxide emission reduction targets in the world, nuclear energy is a promising option for the energy transition [46]. Nuclear plants can provide a reliable and large-scale source of energy, further, no greenhouse gas is emitted during reactions.

D. HYDROELECTRIC POWER PLANTS

Hydroelectric power plants are electricity-producing plants that use turbines to convert the potential energy of moving water into mechanical energy, which is then converted into electrical energy [47]. These plants are usually located in dams that impound rivers, although tidal action is used in some coastal areas [48]. The three types of hydroelectric power plants are run-of-river, reservoir, and pumped storage. In a hydroelectric power plant, water is an essential fuel, and the potential energy is converted into kinetic energy, which is further converted into mechanical and electrical energy with the help of a turbine and motor. The flexibility of hydroelectric plants, especially pumped hydro storage, is becoming increasingly important as grids become progressively dominated by intermittent renewable power generation. Pumped hydro storage power plants can store energy during low-demand periods and release it during high-demand periods, making them ideal for demand response [49]. In addition to electric power generation and grid-related services, hydro-energy power plants are also used for water management, irrigation control for agriculture, water distribution, and/or water waste control.

TABLE 1. Average inertia constant of different power plants [57].

Power plants	Average inertia constant (s)
Nuclear power plants	6.3
Fossil fuel power plants	4
Hydro power plants (conventional)	3
Hydro power plants (small-scale)	1
Wind/solar power plants	0

E. WIND POWER PLANTS

Wind power plants (WPPs), often referred to as wind farms, consist of numerous wind turbines that transform the kinetic energy of the wind into electrical energy [50]. WPPs play a crucial role in the global shift toward RESs. By the end of 2022, the total global installation of wind power capacity reached nearly 940 GW. Furthermore, based on the Global Wind Report [51], an additional 680 GW of wind capacity is anticipated to be installed globally between 2023 and 2027.

WPPs can be located onshore or offshore, connected to the grid via an HVDC system. The increased integration of WPPs into the power grid may present several challenges when they are replacing conventional synchronized generation resources [52]:

- Intermittency of Wind Power: Wind power's variability poses significant challenges to power grid stability. This intermittency makes it difficult to balance power supply and demand because the wind's fluctuation leads to volatile power generation [53].
- Maximum Power Point Tracking (MPPT): Wind turbines [54] or WPPs [55] typically operate under MPPT, optimizing their power output based on wind conditions. This strategy leaves no headroom for supporting additional power during low-frequency events.
- Lack of Inertia: Unlike conventional synchronized generation, the rotational speed of wind turbines is decoupled from the grid frequency by power electronics converters. Therefore, wind turbines cannot automatically provide inertia response and primary frequency response (PFR) to the grid. This decoupling leads to reduced inertia in the grid, which affects rotor-angle stability or frequency stability of the power grid [56]. The average inertia constant of different power plants is given in Table 1.

F. SOLAR POWER PLANTS

Solar power plants (SPPs) use photovoltaic (PV) cells or solar thermal systems to convert sunlight directly into electricity. Solar is rapidly gaining prominence in the global energy transition; installations amount to approximately double the capacity of all other combined renewable technologies [58]. Both wind and solar have similar challenges for the grid connection such as variable characteristics and low inertia for grid support. Compared with the WPP, SPP's generation period is normally easier to predict based on weather conditions and daylight availability. This predictability is beneficial for energy management [59]. However, WPPs can release the kinetic energy stored in the wind turbine's rotating blades by using the new control loops, called inertial emulation [28], which cannot be used by solar panels. WPPs and SPPs are increasingly able to provide an inertial response with advanced control strategies that can maintain grid stability despite their lack of natural inertia [38].

G. ENERGY STORAGE SYSTEMS

Energy storage systems (ESSs) play a crucial role in modern electric grids, especially with the increasing integration of solar PV and wind generation. ESSs are often connected to the transmission grid to enhance grid stability, improve power quality and reliability, and provide backup power [60]. However, various grid-scale ESS technologies are available (e.g., battery storage, pumped hydro storage, flywheel) for the transmission grid [61], and choosing the right technology for a specific application can be challenging, depending on its advantages and limitations as well as intermittent sources. For example, WPP has a ramp rate of megawatts per minute or higher, so an ESS should be selected to match the system's response capabilities and capacity with the variability and ramp rates of the WPP [61].

H. OTHER RENEWABLE POWER PLANTS

1) GEOTHERMAL POWER PLANTS

Utilizing the earth's internal heat, geothermal power plants produce electricity by using steam from heated groundwater to drive turbines. These plants require high-temperature hydrothermal resources from 300°F to 700°F that come from either dry steam wells or from hot water wells [62]. Geothermal power plants are an essential response to the demand for renewable energy. They are a sustainable and renewable source of heat and power that can meet 3%–5% of global demand by 2050 [63].

2) BIOMASS POWER PLANTS

Biomass power plants convert energy from a wide range of organic materials such as wood, agricultural crops and residues, food processing by-products, organic waste in municipal landfills, and human and animal manures [64]. Although each process's sustainability depends on various factors, biomass is considered a RES [65].

3) TIDAL AND WAVE POWER PLANTS

Tidal and wave power plants capture the energy from waves and convert it into electricity using devices called wave energy converters [66]. Waves have the highest energy density of all RESs [67]. Tidal and wave power plants, although less common than other types of power plants, have the greatest potential to be significant contributors [68] to the world's "energy mix resilience" compared with wind, solar, biomass, or geothermal plants.

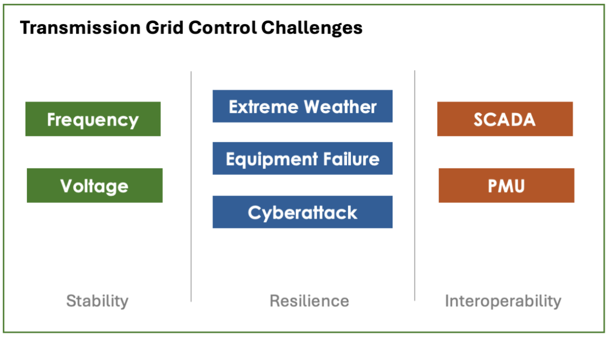

FIGURE 3. Comparative figure for the transmission grid control challenges.

I. FLEXIBLE AC TRANSMISSION SYSTEM DEVICES

Flexible AC transmission system (FACTS) devices are advanced power electronics systems designed to enhance the controllability and increase the power transfer capability of AC transmission lines [69]. Several types of FACTS devices are installed in the grid to enhance stability, improve efficiency, and provide flexibility. For example, static volt-ampere reactive (VAR) compensators (SVCs) inject or absorb reactive power to regulate voltage [70]; thyristor-controlled series compensators (TCSCs) adjust the impedance of transmission lines dynamically [71]; unified power flow controllers (UPFCs) offer the most extensive control, managing real and reactive power flows independently [72], [73]; static synchronous compensators (STATCOMs) [74], [75], which are shunt-connected devices, inject or absorb reactive power to regulate voltage.

III. CHALLENGES IN GRID CONTROL

Grid control faces numerous challenges in the modern world, especially during the energy transition toward RESs such as wind and solar power, which require grid flexibility to accommodate their variability and uncertainty [76], [77]. In Figure 3, the challenges in the transmission grid control is given. Here we mainly focus on the stability, resilience, and interoperability of the control models.

A. GRID STABILITY

The dynamic behavior of power grids has significantly transformed owing to the increased penetration of power electronic converter interfaced technologies such as RESs, storage, flexible AC transmission system (FACTS) devices, HVDC systems, and power electronic interfaced loads. This shift has made the dynamic response of power grids more dependent on complex and fast-responding power electronics devices, possibly leading to new stability concerns [25], [78], [79]. New types of power system stability problems (e.g., converter-driven stability and resonance stability) have been addressed because IBRs have different dynamic behavior than conventional SGs [80]. The stability issues arise from interactions between IBRs' different controls, a reduction in total power system inertia, and limited contribution to short circuit currents from IBRs during faults.

Historically, transient stability has been the dominant stability problem associated with power system transmission reliability [81]. The ability of a power system to maintain synchronism during the few seconds after being subjected to a severe disturbance is known as transient stability [82]. Transient stability control and frequency control are sometimes confused due to their interconnected nature in power systems. While frequency control concentrates on maintaining the grid frequency within an acceptable range following operational changes or disturbances, Transient stability deals with maintaining synchronism among generators following a large disturbance. The conventional method for controlling transient stability involves remedial action schemes. These schemes sense predetermined system conditions and take corrective actions, such as generation re-dispatch, generator tripping, and load shedding. However, the implementation of these schemes is becoming increasingly challenging because of the inertia reduction associated with the influx of IBR on the grid [83]. For example, an increased electrical distance between synchronous generators could weaken dynamic voltage support and reduce the synchronizing torque coefficient [84]. To achieve a high penetration of RESs, it will be critical for IBRs to contribute to maintaining transient stability.

B. GRID RESILIENCE

Grid resilience in the transmission grid refers to the grid's ability to withstand, adapt to, and quickly recover from various types of disturbances, such as extreme weather events [85], equipment failures [86], human errors [87], cyberattacks [88], and other unexpected events. Developing strategies to enhance the grid's ability to withstand and recover from such events is a continuous challenge. Strategies include both physical hardening of infrastructure and the development of resilient communication and control systems.

1) EXTREME WEATHER EVENTS

Climate change has increased the frequency and intensity of extreme weather events, such as lightning, cold and heat waves, hurricanes, wildfires, floods, and severe storms. These events can significantly damage the power infrastructure, including transmission lines, substations, and transformers [85]. Restoring power after such events can be time-consuming and costly and may require robust resources and solutions. Weather conditions in the Nordic region significantly increased grid disturbances, as reported by the European Network of Transmission System Operators for Electricity, and the most significant outages were from extreme weather events [89].

2) EQUIPMENT FAILURES

The North American Electric Reliability Corporation's transmission availability data system reported that equipment failures also contribute to transmission outages is equipment failures [90]. Different equipment failures can lead to unnecessary outages, which will reduce the reliability of the overall power grid. For example, aging transformers are prone to overheating and breakdowns, which can lead to major outages of power grids [91].

3) CYBERATTACKS

With the increased quantity and value of electronic information, cyber threats pose a significant challenge to grid resilience. Those threats normally apply to information communication technologies, industrial control systems, and SCADA systems [92], [93]. A successful cyberattack on the grid's control systems can lead to widespread outages and compromise the safety and security of the grid [94]. Standard network security practices should be used to harden control system integrity by using basic measures of access control, data security, and intrusion detection and mitigation technologies. Additionally, people and process issues must be incorporated to form the minimum basis of a cybersecurity program [95].

C. INTEROPERABILITY

Integrating diverse technologies and systems, especially those from different vendors, requires interoperability standards and guidelines [96]. Smart transmission grids consist of various devices, systems, and technologies, such as smart meters, sensors, advanced metering infrastructure, SCADA systems, PMUs, ESSs, RESs, and various control systems [97]. Those components are often implemented by different vendors and may use different communication protocols and data formats [98]. Facilitating seamless communication and coordination among various devices and control systems within the grid is a significant challenge [99]. Lack of interoperability can lead to problems, including inefficient operation of the grid, increased costs, and service outages. Furthermore, these issues could make it difficult to integrate more RESs into the grid [100].

D. VOLTAGE AND FREQUENCY CHALLENGES

With increasing penetration of RESs (e.g., solar and wind) that are inherently intermittent, maintaining stable voltage and frequency in the grid becomes challenging. Sudden fluctuations in generation can cause voltage and frequency deviations, affecting the reliability of the grid [101].

1) VOLTAGE CHALLENGES

Voltage levels in an electrical grid must be maintained within specified limits to ensure the safe operation of electrical devices and equipment, as shown in Figure 4. From the transmission grid perspective, the main challenges arise when integrating utility-scale wind/PV farms. This integration leads to major transformations of control schemes because the varying rates of RESs are faster than conventional flexible resources. Maintaining stable voltage levels is crucial to preventing damage to sensitive equipment and appliances connected to the grid [39]. Voltage fluctuation, cascading tripping faults, and voltage stability issues [102] such as fault-induced delayed voltage recovery (FIDVR) are main concerns in transmission grids.

Solving these problems requires a better understanding of the interacting mechanism between existing transmission grids and the RES [103]. Last-generation solutions for RES integration have been reviewed [104], and the main issues and perspectives of the integration process were investigated. The investigated integration solutions are classified into innovative materials, new electrical components, advanced electronic devices, automated control systems, smart technologies, and new management mechanics. The increasing rates from RESs require advanced control methods that are adaptive to the RES integration [105]. To enable fast participation of RESs in transmission grids [106], comprehensive coordination between RESs and traditional voltage control devices is made to compensate for the controllability of SGs and SVCs. To immunize against the soaring uncertainty in power systems, a robust optimization approach [107] is proposed, and the risks of voltage violation are mitigated.

Based on past research, the computational burden [108] is a critical concern for the schemes that help mitigate FIDVR. Effectively and economically mitigating FIDVR requires determining the optimal placement and sizing of dynamic VAR sources such as SVCs and STATCOMs as well as incorporating volt/VAR support from IBRs. Placement and sizing are usually solved separately but can be solved simultaneously as a sequence of mixed integer programming problems [109]. For placement, the key is to determine which candidate locations can best improve FIDVR prevention and post-fault voltage recovery. In this study, the system's status could be depicted only by a complicated nonlinear mathematical model, and the differential-algebraic equations may even occur during the post-fault tracking process. The voltage stability in the RES-integrated transmission grids requires more accurate data, which could be provided by the measurement-based approaches using PMUs [110]. For the rapid online voltage stability assessment, Thévenin equivalent parameters [111] obtained by PMUs will significantly enhance the model's accuracy and robustness. A detailed qualitative and quantitative comparative analysis of measurement-based centralized voltage stability monitoring approaches using Thévenin equivalent is presented elsewhere [112]. To simplify the voltage stability analysis, Thévenin voltage and reactance could be assumed as fixed values [113], and a power–voltage curve analysis can be performed to find the voltage collapse point and stability margin.

2) FREQUENCY CHALLENGES

Frequency is a measure of the stability of the electrical grid and is typically maintained at a constant level (e.g., 60 Hz in the United States). Sudden changes in load or generation can cause frequency fluctuations. For instance, if a large power plant goes offline unexpectedly, then an instant drop in generation will occur, leading to a

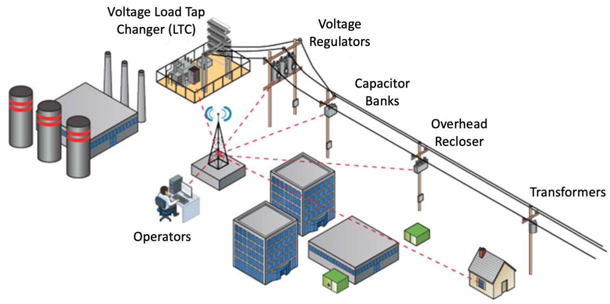

FIGURE 4. Voltage regulation in power systems.

decrease in frequency [114]. By contrast, if a significant load is suddenly disconnected from the grid, then the frequency will increase. Grid operators use various methods to control frequency. Traditional power plants, especially those with rotating generators, provide inertia to the grid, helping maintain frequency stability [115]. However, as more conventional generators are phased out in favor of renewable sources that lack this inertia, frequency control becomes challenging [116].

a: CONVENTIONAL FREQUENCY RESPONSE

Sustained off-normal frequency variations may negatively affect power grid operation, stability, security, and performance. This event may also damage equipment and degrade the operation of relays and protection systems. Depending on the size and duration of frequency variation, different types of frequency controllers are needed to stabilize and restore the power grid frequency. The size of frequency variation refers to the amplitude of Δf, which determines the size of the disturbance and generation–load imbalance. The evolution characteristics of frequency deviation are depicted by the "swing equation" [117], where D is the system damping constant, H is the system inertia constant, and the frequency deviation is determined by the systematic imbalance power ΔP^{imb}.

$$2H\frac{\partial \Delta f\,(t)}{\partial t} + D\Delta f\,(t) = \Delta P^{\text{imb}} \tag{1}$$

The PFR can be provided by any partially loaded generator that can increase (or decrease) output and has a governor. PFR requires rapid response. Traditionally, it is provided by a variety of generators, including hydro and thermal plants, but only a limited subset of the fleet is properly equipped to sustain PFR [118]. WPPs and SPPs can both provide PFR, and wind turbines in some areas are now required to have this capability [119], and the frequency evolution curve after a power imbalance event is shown in Figure 5. However, using variable generation to provide frequency response also has a downside. If an increase in grid frequency is required when a generator is lost, then the affected plants must have been partially loaded in the first place to increase their output. Operating at a partially loaded level (or alternatively, curtailing energy) incurs a cost: curtailed energy cannot be sold into the market. Thus, proper incentives must exist for a variable generation to provide PFR [120], [121]. Primary reserve is a critical product in the ancillary service market. Maintaining operating reserves imposes a cost to grid operations from two primary sources: opportunity cost and movement cost [122]. To provide operating reserves, grid operators must keep a subset of the fleet partially loaded, increasing the number of plants online and reducing overall system efficiency because partially loaded plants are, by definition, not operated at their optimal output. This strategy incurs an opportunity cost for individual generators that could be operating at full output and receiving greater energy revenue. Movement cost is incurred when plants that provide some operation reserve types, such as regulating reserves, are constantly adjusting output to respond to grid conditions. This strategy increases wear and tear costs, and it reduces the generator's efficiency, requiring additional fuel per unit of generation for thermal generators.

However, because SG droops are proportional, the grid frequency will stabilize to a value different from the nominal frequency. Accordingly, the tie-line power flows between interconnected control areas may reach values different from the scheduled ones. During an abnormal operation, depending on the accessible amount of regulation power, a secondary control loop or load frequency control (LFC) system will be activated to balance the power grid frequency and return it to the nominal value. The LFC is the main component of AGC. As shown in the following equation, where ACE is the Area Control Error, the secondary control can attenuate the frequency, and active power changes from 0.1s to a few minutes, where B is the frequency bias in units of megawatts per 0.1 Hz, and Δf is the frequency deviation in steady state. The AGC control logic is built by proportional–integral–derivative control. This control system restores the nominal frequency and the scheduled tie-line power by the allocation of available power reserves.

$$ACE = -10B\Delta f \tag{2}$$

A critical aspect concerning the AGC scheme is the set of activation rules representing how the AGC signals are allocated among generating units, participating in AGC, and subsequently how the secondary control reserves of these generating units are activated. The role of secondary control in restoring system frequency for larger frequency deviation is discussed in the literature [123]: frequency stability and control in smart grids may face new technical challenges arising from the increasing penetration of power-electronics-based loads and generators. Reduced rotational inertia in the grid may adversely affect grid frequency response and system stability and control. Elsewhere [124], the effects of electric vehicles (EVs) on power system frequency regulation are investigated based on an open-source transmission-and-distribution dynamic co-simulation framework.

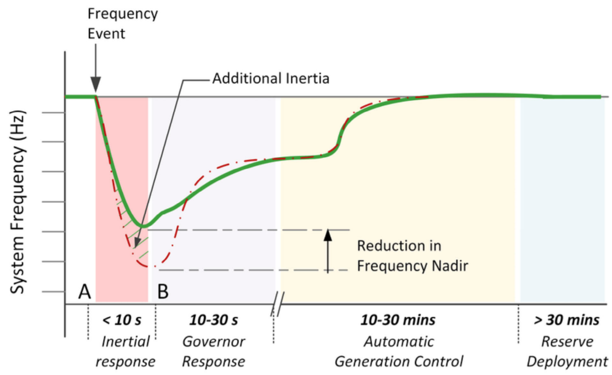

FIGURE 5. Multiple time-frame frequency response in a power system following a frequency event.

b: FREQUENCY RESPONSE WITH RENEWABLE ENERGY SOURCES

As wind and solar plants become more common in the electric power system, they may be called on to provide grid support services to help maintain system reliability. For example, by using frequency response, wind power help balance the generation and load on the system. These active power control services have the potential to assist the electric power system in times of disturbances and during normal conditions while potentially providing economic value to consumers and variable renewable generation owners.

By examining a Japanese grid under different levels of PV penetration, one study [125] shows the importance of considering the system frequency and rate of change of frequency (ROCOF) for grid stability analysis. Another study [102] illustrates how a frequency response constraint can be implemented into production cost models, which are key components of grid planning studies. The complexities and nuances associated with frequency response modeling are also discussed: a case study implementing frequency response in a section of the western US power grid is presented. Fast-responding resources such as battery energy storage systems can rapidly inject or absorb power to balance supply and demand, thereby stabilizing frequency: a capacity expansion model that includes energy storage and PFR is proposed [126]. Including PFR can improve the reliability of the grid and reduce the need for conventional generation. The performance of several frequency response strategies for grid-tied inverters interfaced with RESs have been compared [127], illustrating that droop control is the most effective strategy for providing PFR. These concerns have been evaluated via simulation [128], and a mathematical model was proposed to study the effects of RESs on the frequency of a power system. RESs can significantly affect the frequency of a power system, frequency response can effectively mitigate this impact.

In summary, addressing voltage and frequency control challenges involves a combination of advanced grid monitoring, smart grid technologies, energy storage systems, and demand-side management strategies. By integrating these solutions, grid operators can effectively manage voltage and frequency fluctuations, ensuring the stability and reliability of the electrical grid, even in the face of variable renewable energy generation.

IV. GRID CONTROL TECHNOLOGIES

Control technologies for transmission networks are systems and tools that are used to manage and regulate the flow of electricity within the transmission network [4]. These technologies ensure stable, efficient, and reliable grid operation, handling high-voltage electricity transmitted over long distances from power plants to distribution networks. Feedback control loops are fundamental to grid control technologies for transmission networks. A system's output is measured and controlled to match the desired setpoint, as shown in Figure 6. This process involves sensors, controllers, and actuators working together in a loop to guarantee the system's stable operation and predefined performance. Compared with traditional grid control, the "demand side" should be involved more to be an active role in the control based on grid conditions, prices, or incentives [129]. Table 2 summarizes the shift from traditional grid control to smart grid control, which is driven by the need for a more flexible, resilient, and sustainable electricity system.

A. GRID CONTROL COMPONENTS

The following components offer significant benefits for enhancing smart grid control.

1) PHASOR MEASUREMENT UNITS

Phasor measurement units (PMUs) are critical components in wide-area monitoring systems. They have been deployed across the world and are being continuously upgraded to meet the necessary performance, delivery, and storage requirements [130], [131]. PMUs are high-speed power system devices that can provide synchronized measurements of real-time phasors of voltages and currents [132]. They are also used to calculate attributes such as voltage and current magnitudes, phase angles, and real and reactive power flows. The synchronization is usually achieved by the simultaneous sampling of voltage and current waveforms; a phasor tells the magnitude and phase angle for the AC voltage or current at a specific location on a power line.

The development of PMUs began decades ago and was accelerated when the number of blackouts and outages experienced by the power system increased rapidly worldwide. PMUs can provide measurements at up to 60 Hz—much more than the typical 2 to 4 Hz measurements provided by conventional SCADA systems. Benefiting from the timing signals from GPS satellites [133], the data collected across a grid are synchronized by associating time with data. Therefore, PMUs provide a detailed and accurate view of power quality across a wide geographic grid and tell the system operator whether the voltage, current, and frequency remain within specified tolerances. PMUs are used in multiple ways such as improving the accuracy of modeling system conditions, predicting and detecting stress and instability on the grid, providing information for event analysis after a disturbance has occurred, and predicting and managing line congestion.

In the future, PMUs will become a key tool to make the electric grid more reliable, resilient, and clean [134], allowing for more robust and efficient integration of renewable energy, distributed energy resources, and microgrids.

2) ADVANCED GRID AUTOMATION SYSTEMS

AGC systems automatically adjust the power output of various power plants to regulate the grid frequency to its nominal value in the transmission grid [135]. AGC systems are critical in maintaining the stability of the power grid by automatically adjusting the output of power plants to match the load demand. They primarily ensure that the grid frequency is maintained close to its nominal value (typically 50 or 60 Hz), which is crucial for preventing grid instability that could lead to power failures. Recently, advanced control strategies for AGC systems have been proposed to improve the response of the RES and energy storage [136]. The primary function of the transmission grid control is energy management. This system continuously receives and displays measurements—including system frequency, circuit breaker status, voltage levels, and power flow through transmission lines and transformers—from various assets at short intervals (typically spanning just a few seconds) [137]. Generally, SCADA systems are used for real-time monitoring and control of components in transmission grids from a central location [11]. SCADA systems can provide operators with a comprehensive view of grid operations, enabling quick response to disturbances or outages [4]. The wide-area monitoring, protection, and control (WAMPAC) system is a comprehensive way to monitor, protect, and control large-scale power systems, thereby enhancing the reliability, efficiency, and safety of transmission grids [18], [138]. WAMPAC systems can solve low-frequency, inter-area power oscillations, which are critical issues in large interconnected transmission grids when the penetration level of RESs increases [139].

3) ADVANCED COMMUNICATION NETWORKS

To implement advanced grid automation systems technologies for real-time control, advanced communication networks are crucial to reliably, efficiently, and securely manage a grid [140]. They can facilitate real-time control and decision-making by ensuring that data from various parts of the grid, such as the substations and transmission grid, is communicated to control centers without significant delays [141]. The performance of PMU-based real-time control and monitor applications is significantly affected by the latency in data transmission between substations and control centers, so advanced communication networks are important. Furthermore, studies and simulations [142], [143], [144] have shown that even minor latencies introduced

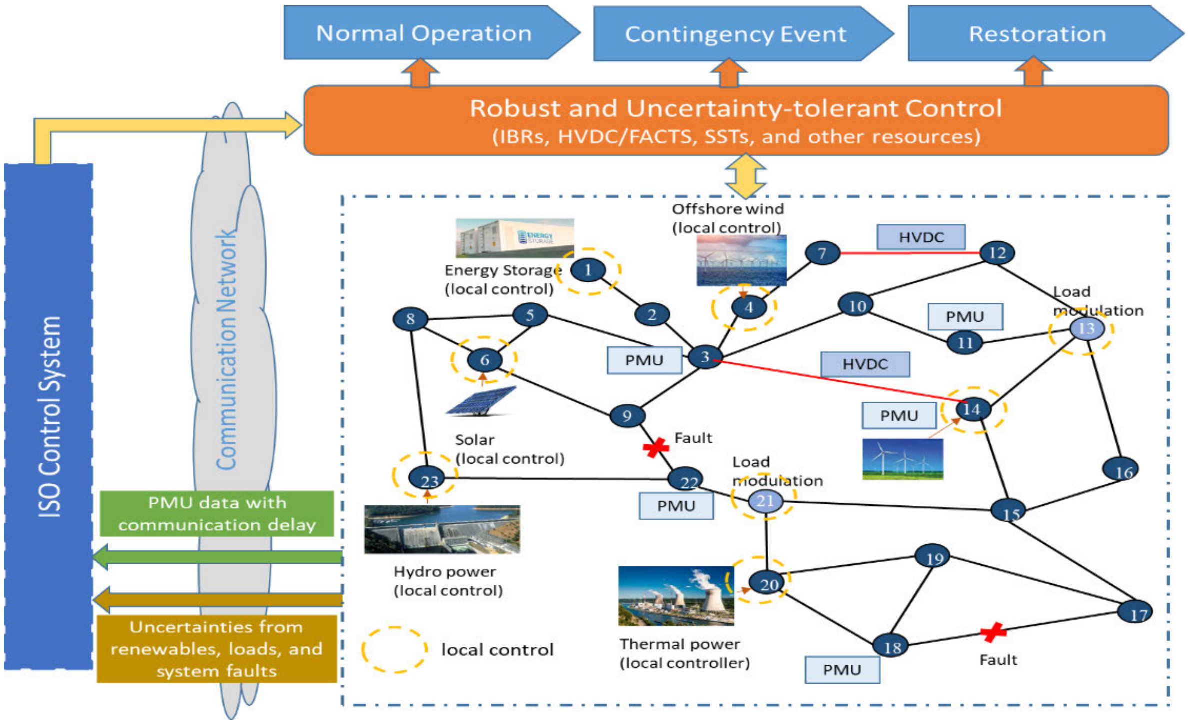

FIGURE 6. Grid control technologies for transmission networks.

TABLE 2. Key differences between traditional and smart grid control.

	Traditional grid control	Smart grid control
Generation	Relies primarily on large, centralized power plants	Incorporates a wide range of generation sources (decentralized and distributed)
Power flow	Power flows in one direction, from generation plants to consumers	Bi-directional power flows, allowing greater flexibility and interaction
Data utilization	Decisions were based more on historical trends	Forecasting and real-time monitoring
Consumers	The demand side of the grid (consumers) played a passive role	The demand side is more actively involved
Role of renewable energy:	Unidirectional flow from large, centralized power plants	Advanced technology for effectively integrating and managing RESs.

by inadequate network technologies and architectures can disrupt critical grid functions, such as mitigation measures for power system oscillation. These disruptions can lead to inefficient damping for oscillations, potentially causing instability or failures in the power grid. Therefore, ensuring minimal delay is crucial for the effective functioning of these applications [145]. To address these challenges, it is imperative to use advanced communication technologies capable of delivering low-latency and high-reliability performance. Technologies such as fiber optics, 5G/6G wireless networks, and dedicated broadband networks for utilities may meet these requirements.

B. MODELING

Power system modeling is a crucial process in the field of grid control. It involves creating mathematical representations that accurately depict the behavior and characteristics of different components within a power system such as generators, transmission lines, transformers, loads, and control systems. These mathematical models enable engineers to analyze and simulate the performance of the power system, facilitating controller design and optimizing system operation.

1) SMALL-SIGNAL MODELING

AC power electronics systems are widely found in modern power grids because of the large-scale integration of renewable energy resources and flexible DC and/or AC transmission systems. The dynamic interactions of power electronics systems may lead to resonances and abnormal harmonics across a wide frequency range [146]. Consequently, modeling and analyzing the dynamics of converter-based power systems are of paramount importance. Small-signal modeling is a mathematical technique used to approximate the behavior of a nonlinear system by linearizing it around a specific operating point [147]. The harmonic state space (HSS), the dynamic phasor, and the Generalized dq (GDQ) modeling are three popular methods for small-signal analysis of AC power electronic systems.

The HSS modeling method characterizes the frequency domain dynamics of linear time-periodic systems [148], and thus a prior linearization around the steady-state trajectories is required [149]. The HSS model yields a harmonic transfer function in the frequency domain, which is, essentially, a linear time-invariant transfer function matrix, revealing dynamic couplings between the Fourier coefficients of harmonics.

The dynamic phasor modeling is derived from the generalized averaging (GA) operator [150]. Given a fixed system fundamental frequency, the GA operator calculates the Fourier coefficients of time-periodic variables over a moving time window, and thus the time-periodic system can be represented by the differential equations of multiple time-invariant Fourier coefficients. Then, the linearization around their equilibrium points can be performed [151]. This method has been widely applied to model power converters in three-phase unbalanced grids [152], or with multiple harmonics. The GA operator can be applied in any reference frame wherever the system is time periodic, and it can be represented by either real or complex variables.

The GDQ modeling method is developed based on the GDQ transformation theory [150]. The GDQ transformation allows for modeling the time-periodic system in multiple dq frames, where only the dynamics around the time-invariant operating points need to be considered, which can be achieved by further applying a state-space averaging (SSA) operator. The idea was initiated to model an unbalanced ac system [153]. However, this multiple dq-frame model overlooks the couplings between different dq frames because of the time-periodic nature of the resulting systems in each dq frame.

2) LARGE-SIGNAL MODELING

Large-signal modeling, also known as transient or dynamic modeling, is another important technique in grid control applications [154]. The technique involves detailed modeling of various power system components, including generators, transformers, transmission lines, IBRs, loads, and control systems (e.g., voltage regulators and speed governors) [155]. Each component's dynamics are represented by differential-algebraic equations, which together formulate the system's dynamic model, especially for nonlinear dynamics [156]. Large-signal modeling is used primarily for transient stability analysis considering large disturbances [157], [158], [159]. Understanding and addressing the stability issues in power electronics-dominated power systems is crucial to ensure the reliability and efficiency of smart transmission grids, especially those with a high penetration level of RESs [36], [160]. For example, one study [161] addresses the large-signal mathematical modeling and dynamic analysis of a hydro-energy generation system in the transient of sudden load increasing. Another study [162] addresses the transient stability of voltage source converters regarding the fault ride-through scenarios in the power grid with high penetration of RESs.

3) DATA-DRIVEN MODELING

Modern power grids are rapidly evolving with increasingly volatile renewable generation, distributed energy resources, and time-varying operating conditions. The structure of data-driven modeling in power systems is shown in Figure 7. The grid control is confronted with low inertia, uncertainty, and nonlinearity that challenge the operation security, efficacy, and efficiency [163]. The ongoing digitization of power grids provides opportunities to address the challenges with data-driven modeling and control [164]. The advanced sensing infrastructures (such as phasor measurement units and smart meters) supply much more complicated and specified data and the energy resources can be coordinately controlled to realize different operation objectives [165] at different levels and timescales in a model-free data-driven fashion.

To mitigate the induced operational challenges, numerous efforts has been made by applying or promoting data-driven control methods for different cases. In voltage control aspects, one method [166] does not require any model knowledge to estimate the sensitivity matrices by using PMU data online. When tuning the controller for an independent power grid, another data-driven method [167] identifies the frequency response directly to tune the robust controller of grid-supporting battery energy storage systems. For larger disturbances, another model [168], [169] suppresses the critical inter-area modes of large-scale power systems by selecting the most suitable SGs for control via the proposed algorithm. Under extreme events, the data-driven methods are applied to study the resilient control of linear time-invariant [170] systems against denial-of-service attacks. For demand response, a model-free operation strategy is promising when leveraging the recent developments in reinforcement learning because scalable demand response of residential electric loads has been a timely research topic in recent years.

From the methodology perspective, the data-driven control can be classified as linear system control and nonlinear system control. In power grid applications, the identified linear transfer function can be applied for different purposes such as (i) tuning, design, and testing of power system control systems such as power system stabilizer, SVC, and many others [171], [172] and (ii) validation of power system small-signal models for grid planning and operation [173]. Different transfer functions can be identified to address different potential operating conditions, whereby robust controllers can be designed accordingly. Nonlinear identification requires more advanced methods. Supervised learning [174] is a powerful way to fit the non-linearity of universal learning machines, but it is often used for nonlinear dynamic modeling without external control. Reinforcement learning is another branch of machine learning that inherently bridges control and mainly relies on offline simulators. This strategy is

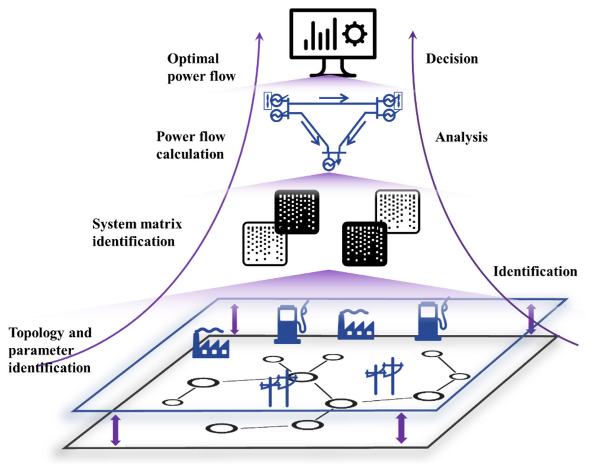

FIGURE 7. Data-driven modeling in power systems.

gaining popularity for applications of data-driven control of power grids [175], [176].

4) HYBRID MODELING

Although the pure data-driven methods discussed previously can fit any linearity or nonlinearity, areas for improvement remain. First, their strict reliance on historic data [177], which remains limited under severe conditions, hinders capturing data characteristics under new circumstances. Furthermore, although the existing methods incorporate information on events' density and type, they do not include structural system-wide information [178]. To this end, hybrid physics-based modeling has been employed, typically using simulation methods to develop the model characteristics considering multiple input parameters [179], [180]. The advantages of hybrid physics-guided machine learning techniques have been addressed elsewhere [181], and the combination can surpass conventional metrics of accuracy. Considering the false data injection attacks, other models [182], [183] exploit the data-driven machine intelligence working with current bad data detection methods, overcoming the vulnerability of conventional physics-based state estimation. For prediction study, the derived physical models are enhanced and modified by the data-driven prediction models [184], [185].

However, such mechanistic blueprints rely on many assumptions and cannot capture the complex interactions among the various operational conditions, system uncertainties, and the mass data collected by advanced devices. In this sense, the combination of physics-based and data-driven models is promising. Whereas the structural reliability approach implements physics and engineering concepts for predictions while failing to capture the more convoluted extreme events factors, the data-driven approaches integrate a wide array of variables while suffering from data scarcity in extreme and rare conditions [186]. Therefore, integrating the fragility analysis with the machine learning–based prediction models could provide several key improvements. Provided the limited historical data on physics-based models, using machine learning or statistical methods have been proposed [187] and coupled with data-driven technologies [188].

In summary, each of the four modeling methods has its own set of advantages and disadvantages, as shown in Table 3. Choosing the best modeling method depends on the specific application and requirements.

C. CONTROL METHODS

1) CENTRALIZED CONTROL

Centralized controllers have a structure that provides access to comprehensive information about the entire system, as shown in Figure 8. Therefore, they can calculate and implement global optimal solutions that effectively optimize overall grid performance. Moreover, centralized control enables efficient coordination of various controllable components of the entire grid, ensuring stability and mitigating the risk of cascading failures.

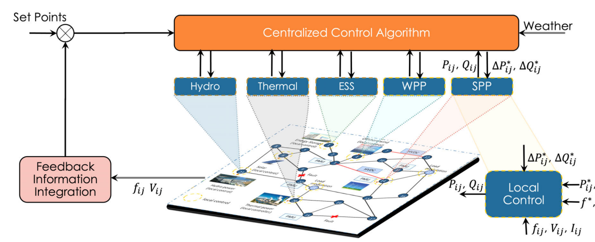

FIGURE 8. Centralized control technologies for transmission networks.

A novel adaptive method for secondary voltage control in transmission grids has been proposed [189]. The method uses synchronized PMU data, formulates the voltage control problem as a nonlinear constrained optimization problem, and uses a successive approximate vector ∞-norm minimization algorithm to determine the optimal control action. The proposed method is adaptive in the sense that it can estimate load disturbances online to compute the feasible control action to minimize the worst-case load voltage deviation. Simulation studies on various IEEE benchmark systems, including the IEEE 30-bus system, demonstrate the feasibility and effectiveness of the proposed method. Another method using PMU data has been designed to provide real-time visualization of voltage stability, possibly improving situational awareness and decision-making capabilities for system operators [190]. A model-free wide-area voltage control method has been proposed to provide an effective and flexible online voltage control solution for power systems using PMU data and collaborating with the IBRs [191]. By using a modified IEEE 68-Bus system, the model-free method demonstrates robustness to issues such as topology changes, measurement noise, and missing PMUs. However, it may introduce complexities in the implementation of large-scale power systems. A data-driven method using PMU data has been designed for real-time static voltage stability assessment. This method is robust to load changes and improves computational efficiency compared with a singular

TABLE 3. Power system model methods and their advantages and disadvantages.

Modelling type	Focus	Approach	Applications	Strengths	Weaknesses
Small-signal:	Small deviations around operating point	Linear equations	Stability analysis, control design	Simple, efficient, good for local behavior	Limited accuracy for large disturbances, ignores nonlinearities
Large-signal:	Large deviations nonlinear phenomena	Nonlinear equations numerical methods	Transient stability, faults analysis, control design	More accurate for large disturbances, captures nonlinearities	Complexity, sensitive to parameter uncertainty
Data-driven:	Learn relationships from data	Machine learning algorithms	Forecasting, optimization, cybersecurity	Handles complexity, adapts to changes, learns from data	Requires large data, lacks interpretability, sensitive to trained data
Hybrid:	Learn relationships from data plus physical understanding	Data-driven plus equations	Forecasting, optimization, control strategies, cybersecurity	Improved accuracy, physical interpretability, adaptability	Requires large data, complexity

value decomposition–based approach [192]. However, those methods heavily rely on the accuracy and availability of PMU data. Time delays from PMUs also affect grid stability during contingencies for the controller [193].

An optimization problem for voltage control has been solved to minimize reactive power output. The solution coordinates IBRs with traditional resources, such as SGs and FACTS devices [194]. Using a modified New York State grid as a case study, the proposed method has been shown to enhance grid stability and efficiency with increased IBR penetration. A wide-area controller has been designed to diminish low-frequency oscillations by considering various channels of communication with stochastic delays [195]. The proposed method uses wide-area measurements and formulates the control problem as a deep deterministic policy gradient and improves the system stability under different communication delays in Kundur's 4-generator system and 10-generator New England system.

Compared with model-based controllers, data-driven methods can eliminate the need for exact grid models, so the approaches are adaptable to various grid configurations and changes. The scalability in wide-area control has been solved by reducing learning time and computational complexity [196]. Using the IEEE 68-bus system, the proposed scheme has been shown to be effective: oscillation damping and performance were improved under various conditions.

A novel strategy for fast prediction of remedial control actions (RCAs) has been designed to prevent transient instability in emergency events, where the RCA is an important scheme to maintain the stability and reliability of transmission grid systems [197]. The accuracy of the proposed method was validated using the IEEE 39-bus system and the 74-bus Nordic test system. However, those data-driven methods rely on the quality of data, and their complexities may pose implementation challenges.

In modern power systems, characterized by complex interconnected networks and renewable energy sources, necessitate innovative approaches for protection and control [198]. Depending on the time of actuation, control methods to maintain stable system operation are classified into two categories, namely the preventive control and corrective control. The existing corrective control methods are response-driven (e.g. under voltage load shedding and under frequency load shedding), which act as the final resort for system stabilization. The work in [199] proposes a risk-averse deep learning method for real-time emergency load shedding, which trains a deep neural network towards the reluctance to load under-cutting events, so as to avoid the huge control cost incurred by control failure. Corrective control models are often framed as constrained optimization problems, and there is growing research interest in using machine learning techniques to solve these problems in real-time [200]. The event-driven corrective control method, also referred to as emergency control, aims to provide in-time system performance improvement by executing immediately after contingencies. Among the common emergency control methods, emergency load shedding immediately cuts off a certain amount of load after contingencies, which has been identified and widely adopted as an effective and fast method to stabilize the system [201]. In [202], energy storage systems and emergency load shedding are adopted to ensure stability when minimizing the system costs. Indeed, many efforts have been made in the fields of emergency voltage and frequency control. In [203], a hierarchical data-driven method is proposed for the online prediction of event-based load shedding against fault-induced delayed voltage recovery. Authors in [204] propose a profitable and flexible Virtual Power Plant recruitment-participation approach that incorporates both long-term regular recruitment and short-term casual recruitment. HVDC system acts as a flexible device in the power system and also provides promising controllable sources to the grid. For example, [205] introduces a closed-loop emergency control scheme to enhance the system security. Furthermore, considering the higher penetration of wind power in power systems, [206] proposes a stability mechanism and emergency control theory, where the trajectory encountering a singular point of the differential algebraic equations corresponds to transient voltage instability in the system. A unified approach for transient stability enhancement following large disturbance is proposed in [207] through preventive or/and emergency control measures.

A co-optimization method between transmission and distribution systems has been designed for regulating voltage

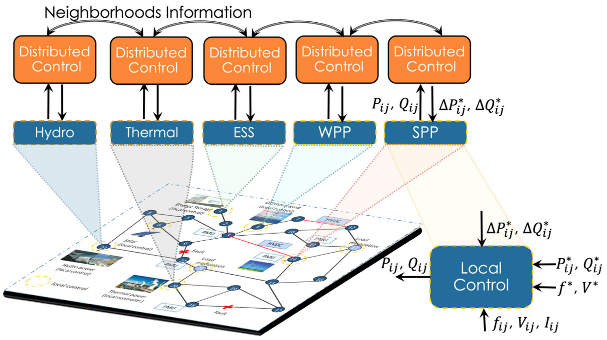

FIGURE 9. **Distributed control technologies for transmission networks.**

at distribution systems while fulfilling transmission system DR [208]. The proposed algorithm has been validated by using the IEEE 123-bus system. However, the effectiveness of the proposed approach depends on the availability of accurate and timely data, which serves as the foundation for successful implementation.

2) DISTRIBUTED CONTROL

Distributed control is an increasingly important approach to managing various generation resources in power grids [209]. Unlike centralized control, distributed control technologies operate autonomously based on local information and communication with neighbors in the local controller, as shown in Figure 9. Distributed control technologies have various benefits such as scalability, adaptability, resilience, and reduced communication requirements.

A novel distributed control framework has been proposed to improve the resilience and transient stability of smart power transmission systems in the face of disturbances [210]. The proposed framework integrates traditional governor-based power control with ESS-based controls, thereby mitigating insufficient capacity or absence of ESS. The proposed method was validated in the IEEE 68-bus test system, which shows that the system can adapt and recover from both cyber and physical disturbances. However, the performance of the proposed framework depends on the capacity and availability of the ESS. Limitations in the ESS technology, such as ESS capacity, efficiency, and lifespan, may limit the overall efficacy of the framework.

Taking into account the stochastic characteristics of the operation of the power system and RESs, a stochastic distribution control model has been designed to handle frequency variations in power grids by optimizing the probability density function frequency [211]. The IEEE 3 machine 9 bus system that includes one wind was used to validate the effectiveness of the proposed method, where both the mean value and variance of the probability density function are significantly reduced (i.e., a robust optimized solution with a minimized mean cost is obtained). However, the success of the method may depend on the precise modeling of the stochastic characteristics of power systems, especially in RESs.

Distributed control frameworks generally partition the whole system into several smaller subsystems. Each subsystem corresponds to a subproblem, which could be solved more efficiently and coordinately to obtain an equivalent optimal solution [212]. All subproblems could be solved simultaneously parallel by using high-performance computing techniques [213], which can further enhance the computational performance of distributed control. However, owing to difficulties in allocating tasks to individual processing units by partitioning [214], the technology is mostly limited to solving large-scale linear and nonlinear equations in the transient stability based contingency analysis [215]. A distributed control method has been proposed to improve the voltage profile by using measurement-based voltage sensitivities [216]. This approach utilizes real-time PMU data to build multiport equivalent models of the power grid. These models are then used to derive measurement-based voltage sensitivities and system transmission capability sensitivities.

A distributed control strategy that utilizes the information from neighboring nodes through sparse communication networks is proposed to improve transient stability in transmission grids with intermittent and low-inertia renewable energy sources [217]. The distributed control strategy enables better management of dynamic stability and is suited for large-scale systems where centralized control may impose significant communication and computation burdens. Paper [218] introduces a hybrid control strategy combining local, distributed, and event-triggered control mechanisms to improve system resilience. The proposed method allows control agents to act on local data initially and seek assistance from neighboring agents when local resources are saturated. The control strategy has been validated using a modified PJM 5-bus system from [219] to ensure safe operation. A unified distributed secondary controller is proposed to manage frequency and voltage at the point of common coupling for battery storage across different grid conditions [220]. It provides a sufficient condition for the upper bound of communication delays between storage systems to ensure system stability. The effectiveness of the proposed method has been validated via a modified IEEE 118-bus system with 54 generators, 91 loads, and 54 BESS units.

Three new distributed controllers are proposed to enhance control ability in multiterminal HVDC transmission systems [221]. These controllers are designed to maintain voltage stability and minimize power loss while ensuring efficient power distribution among multiple terminals. The proposed controllers are validated on a four-bus multiterminal HVDC system to demonstrate their ability to provide stable voltage control and optimal power distribution with practical settings. In addition, a distributed frequency control method is developed for multiterminal HVDC transmission systems [222]. It combines decentralized and distributed control techniques to ensure robust and scalable frequency control across various AC grids connected via multiterminal HVDC transmission systems

A novel hybrid control architecture that integrates the speed and security of fully distributed control with the extensive system visibility provided by centralized control is proposed to enhance the system's responsiveness and reliability under high renewable penetration [223]. The proposed method can significantly reduce frequency deviations and enable better management of the larger fluctuations and ramping events with high levels of intermittent RESs. The effectiveness of the proposed control methods is validated using a detailed transmission model of the Bonneville Power Administration.

In summary, distributed control technologies offer several benefits, including scalability, adaptability, resilience, and reduced communication requirements. However, each distributed controller must make decisions based on local information and communication with neighbors. This strategy requires sophisticated algorithms that can handle incomplete information, adapt to changing conditions, and cooperate to achieve global objectives.

3) DECENTRALIZED CONTROL

With the increasing size of power systems and the complexity of various kinds of energy resources, centralized control may not be able to handle the increased computation and communication problems [225]. Decentralized control, as an alternative approach to solve the challenges of the centralized optimization mechanism, has attracted increasing attention recently. It offers more scalability for larger and more complex systems.

From the communication perspective, the decentralized control framework also has its advantages. Considering the privacy issues between entities, the communication requirement could be significantly reduced when only limited information is needed [224]. Furthermore, in some adjacent subregions, full information is private and is not supposed to be exchanged, but a central controller is able to get access to all information [226]. Moreover, compared with the centralized method, the decentralized optimization framework is more flexible and adaptive with respect to system changes. This flexibility is important, especially because the topology of the electricity grid and the communication infrastructure in the smart grid are likely to be more dynamic [227].

A smart self-healing method for voltage control has been proposed. This method uses master and local control agents [228]. One local control agent with a performance index is assigned to each subsystem, and it uses a fuzzy system to intelligently select and apply control actions when the performance index exceeds its threshold. The master control agent, in the second step, optimizes the power system state by solving an optimization problem. The proposed method was tested on a 39-bus New England system, in which it demonstrates effective performance, including improved decision-making speed and efficiency. However, the multiagent system approach may introduce complexity in terms of coordination and communication between agents. Coordinated economic dispatch and optimal power flow solutions between transmission and distribution grids are required to maximize operational benefits and mitigate issues (e.g., overvoltages and power flow instabilities) [229]. A novel decentralized method for solving transmission and distribution grids AC optimal power flow [230] has been proposed to consider active distribution grids that integrate more distributed generators and RESs. Two IEEE test systems (a 14-bus transmission grid with three 69-bus distribution grids and a 118-bus transmission grid with thirteen 69-bus distribution grids) were used to show efficient power generation and distribution [231]. However, managing nonlinearity may demand significant computational resources. A decentralized coordination approach between transmission system operators (TSOs) and distribution system operators (DSOs) for voltage regulation has been proposed to increase RES penetration in distribution grids [232]. Simulation studies via Slovenian TSO and DSO grids demonstrated [233] that effective regulation of high voltage is obtained by managing reactive power injected by different RESs. However, the analysis and coordination process may require significant computational resources [234].

In summary, decentralized control offers promising potential to address the challenges of managing large and complex power systems. For example, the decentralized methods can enhance system resilience by avoiding a single point of failure and efficiently managing the computational load. In addition, the decentralized nature of the solution makes it scalable and adaptable to different grid sizes and configurations. However, the decentralized control methods often yield suboptimal solutions instead of globally optimal ones. Furthermore, designing and implementing efficient and robust decentralized control algorithms for large-scale power grids can be challenging, especially as the system size and complexity increase.

D. TECHNICAL IMPLEMENTATION

The complexity of implementing advanced power system control methodologies is noteworthy due to: (i) the increasing penetration of RESs that raises higher requirements for stability and reliability during implementation; (ii) evolving transmission grid patterns introduce more challenges to the implementations; (iii) digitalization-based power grid communication systems introduce time delays that cannot be neglected. In [235], the authors summarized the technical control solutions to address the power system stability challenges regarding the large-scale PV integration into the transmission systems. The future power system has to deal with not only uncontrollable demand but also uncontrollable generation. Furthermore, the loss of auxiliary devices will have a significant impact on system stability. The research effort in [236] attempted to investigate and solve the potential controller interaction issues in sub-transmission/distribution systems with high penetrations of PV and wind generations. Regarding the centralized renewable energy generators control theories, [237] and [238] studied the impact of control

TABLE 4. Summary of research in transmission grid control.

Ref.	Devices	Control method	Objective	Validation
[189]	PMUs, reactive power sources	Centralized secondary control	Improve the voltage profile	IEEE 9-bus and IEEE 14-bus test systems
[190]	PMUs	Online loading margin estimation	Fast and adequate for online voltage security assessment	IEEE 14, 30, 57, 118, 300-bus systems
[191]	PMUs, IBRs	Model-free wide-area damping control	Damp inter-area oscillations	IEEE 68-bus system
[192]	PMUs	Data-driven approach	Real-time static voltage stability assessment	IEEE 118-bus, 300-bus, Polish 2383-bus systems
[193]	PMUs, FACTS	Wide-area monitoring and control	Improve the voltage profile	Hardware-in-the-loop
[194]	IBRs, FACTS	Gradient-descent-basted voltage control	Improve the voltage profile	Hardware-in-the-loop (5000-bus NY state grid)
[195]	PMUs, RES	Reinforcement learning based wide-area damping control	Damp down low-frequency oscillations	Kundur's 4-generator and 10-generator New England systems
[196]	PMUs	Reinforcement learning based wide-area damping control	Update the control gains whenever a significant load occurs.	IEEE 68-bus system
[197]	Offline dataset	Machine learning-based RCA	Predict the stability, generator coherency, and RCA	IEEE 39-bus and the 74-bus Nordic systems
[198]	IBRs	Emergency control	Enhance transient stability against wind power uncertainty	IEEE 39-bus system and Nordic 32 system
[208]	Demand response	Coordinated voltage control	Minimize voltage deviations at the lowest cost	IEEE 123-bus system
[210]	ESSs, frequency response	Distributed control	Enhance transient stability	IEEE 68-bus system, 3-generator 9-bus system
[217]	Sensor of synchronous generators	Distributed model-free controller	Enhance transient stability and robust to uncertainties	IEEE New York-New England 68-bus system
[220]	Battery storage	Distributed secondary controller	Manage frequency and voltage, and share powers of battery storage	IEEE 118-bus system with 54 generators, 91 loads, and 54 BESS units
[222]	Converter of HVDC	Distributed frequency controller	Ensure robust and scalable frequency control	Multiterminal HVDC transmission systems
[224]	PMUs, RES	Decentralized control	Computational and communication scalability	IEEE 118-bus transmission grid and thirteen 69-bus distribution grid

methodologies to the voltage regulation and loss reduction, the efforts were devoted to addressing the harmonic control problems when integrating RES [239].

Facing the growth of modern transmission grid frameworks, such as advanced demand response programs [240], real-time implementation of measurement-based control mechanisms [241], and smart infrastructure [242] are the critical solutions to the challenges induced by the fast-changing topology, energy portfolio, and consumer behaviors [3].

Communication technologies have superseded systems in power systems. Various high-performance wireless technologies are implemented for remote monitoring and controlling of loads [243]. There have been extensive works on disparate layouts of communication infrastructures in the smart grid by surveying feasible wired or wireless communication technologies, such as big data management in power systems [244], advanced internet implementation approaches for things-enabled smart grid [245], and enhanced sensor networks deployment methodologies for power delivery systems [246].

V. CURRENT INDUSTRIAL PRACTICES AND FUTURE OPPORTUNITIES

A. CURRENT INDUSTRIAL PRACTICES

When various countries connect their power plants to the European transmission network, inter-area frequency oscillations can occur. These oscillations can make the electricity system unstable and cause reliability issues, which might cause power plants to shut down unexpectedly and could lead to the separation of the transmission network. Since 2016, French and Spanish TSOs have collaborated to create and implement a procedure for managing the border of Franco-Spanish HVDC lines [247]. This effort aims to tackle the inter-area oscillations. In the Nordic power grid, more RESs will be integrated into the grid, and a unified European framework encompassing dynamic market, operational strategies, and planning processes will be expected [248]. These structural changes may present significant challenges to the operational and planning aspects of the Nordic power system. To enhance the flexibility of the system, generation adequacy, frequency quality, inertia, and transmission adequacy are needed. Today, the Nordic TSOs use the following solutions to solve these challenges [249]: (1) ensuring a high level of market capacity while maintaining reliable operational standards, (2) striving for a balance that leads to newer and more efficient system operations, and (3) establishing a robust foundation for the development of the future power grids. In the Icelandic grid, as loads and generations continue to grow, the issue of angle stability during disturbances increasingly poses risks of islanding and subsequent outages. To address these dynamic challenges, rapid location-sensitive balancing control using real-time WAMPAC has been implemented. This strategy reduces both the frequency and severity of islanding events in Iceland [250]. In the Greek power grid, 15 time-synchronized

PMUs, which are placed in critical locations, gather data for real-time monitoring and control of the power grids to manage the challenges from the high penetration of RESs [251]. The German TSO has committed €1.9 billion to replace aging infrastructures. This investment ensures the long-term reliability and stability of the German and Dutch grid [252].

In recent years, FACTS and ESS devices have increasingly been used as actuators of WAPMAC systems [139]. The FACTS device has been strategically deployed and tested on the network to minimize congestion and increase cross-border capacity on congested transmission lines between Greece and Bulgaria [253]. This technology enables faster integration of renewable energy and reduces curtailment of RESs. An Australian TSO recently upgraded the Victoria–New Sout Wales interconnector with the latest FACTS technology, unlocking an additional 170 MW of energy [254]. ESS optimally exploits its capacity to provide ancillary services to the connected TSO with WPPs [255].

HVDC technology enables the efficient and reliable transmission of renewable energy, enabling the delivery of substantial amounts of high-quality electricity. HVDC technology will be used for interconnection between Québec City, Canada, and New York City, United States. The link will enable the delivery of clean, renewable hydropower between the two areas [256]. This technology also can tackle the inter-area oscillations [247]. The United Kingdom will construct two HVDC converter stations with HVDC subsea transmission cables to transfer RESs to more than two million homes between Scotland and England [257].

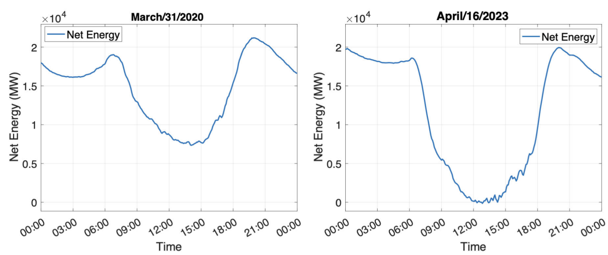

FIGURE 10. Net demand that system demand minus wind and solar in 5-minute increments on 03/31/2020 and 04/16/2023.

As of January 2023, the United States had 73.5 gigawatts (GW) of utility-scale solar capacity and 141.3 GW of wind capacity in operation [258], which accounted for approximately 6% and 12% of the United States' total energy capacity, respectively. As a result of the growing integration of RES, the net energy has transitioned from a "duck curve" to a "canyon curve" [259], as illustrated in Figure 10 (data from [260]). One of the possible solutions to solve this issue is to increase the flexibility of the grid. Flexibility in both transmission and distribution grids is crucial for effectively integrating RESs and ensuring grid stability in a future grid driven by clean energy. Figure 11 presents a variety of potential solutions for flexibility, spanning from short- to long-term [261]. To maintain the balance between electricity supply and demand on the Texas grid, the independent system operator procures ancillary services in the day-ahead market [262]. These services are provided by generators or consumers to mitigate real-time operational issues and ensure the smooth and reliable operation of the grid. In the California grid, the independent system operator procures flexible ramping products to enhance grid reliability and market performance [263]. By acquiring upward and downward flexible ramping capacity in the real-time market, these products help manage the volatility and uncertainty in demand and supply.

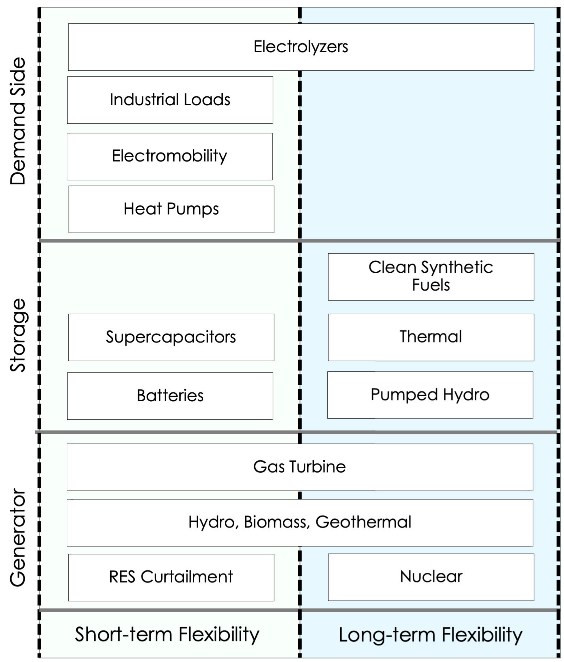

FIGURE 11. Short- and long-term flexibility solutions in the active transmission and distribution grids.

In the United States, as the penetration of advanced meters rises across the country, many state regulators are initiating proceedings in anticipation of additional advanced meter deployment proposals [264]. Paper [265] describes the design and implementation of the first wide area control system in North America that uses real-time PMU. The control system utilizes real-time PMU feedback to construct a commanded power signal which is added to the scheduled power flow for the Pacific DC Intertie to damp inter-area oscillation. This controller has been implemented in hardware and successfully tested in both open and closed-loop operations. The main finding is that the controller adds significant damping to the modes of the western interconnection and does not adversely affect the system response in any test case. In addition, some state regulators have characterized advanced meter deployment proposals as having incomplete or speculative benefit calculations and have required greater demonstration of costs and benefits in utility proposals. Changes and new proposals by utilities in some states may be in response to those concerns. For example, state regulators in Connecticut and New Jersey initiated proceedings that provide initial clarity on how they expect utilities to unlock value from advanced meters and analyze the costs and benefits of advanced meter deployment [266]. The request for proposals instructed utilities to present details on their advanced metering starting point, the business needs and value that full deployment of advanced meters will unlock, data and analytical tools to deliver operational efficiencies of advanced meters, and how advanced meters will enhance demand reduction strategies, among other state strategies [267]. Additionally, for the District of Columbia, the Public Service Commission (DC PSC) reconvened the Customer Impact Working Group to resolve issues raised in a Potomac Electric Power Company report on the feasibility of providing customers with access to energy usage data in a standardized, consumer-friendly format [268]. On September 9, 2021, the DC PSC directed the working group to prepare a report, within 90 days, including a timeline and cost estimate for implementing a "Connect My Data" platform. In August 2018, the Minnesota Public Utilities Commission (Minnesota PUC) directed Xcel Energy's Northern States Power Company (Xcel Energy) to file annually an Integrated Distribution Plan [269]. In November 2019, Xcel Energy filed an Integrated Distribution Plan, which included a proposal to install 1.3 million advanced meters throughout its service territory. The compliance filing also noted that advanced meters are a key enabler for more complex rate structures, such as a three-period design in its time-of-use rate pilot, interactive demand response rate offerings, and critical peak pricing.

One of the main barriers to the deployment of advanced power grid control methods is the lack of standards for communication and data exchange between different control systems. The US Department of Energy Advanced Synchrophasor Protocol Development and Demonstration Project [270] began on May 1, 2017, with the objective to standardize a protocol (IEEE 2664) for streaming telemetry transport that could overcome existing protocol limitations such as scalability, bandwidth requirements, and transport security. Knitting together equipment vendors, utilities, reliability coordinators, and other industry stakeholders is a significant task and remains a risk to wide-scale deployment.

B. FUTURE OPPORTUNITIES

In the latest Annual Energy Outlook (projected based on the reference case that assumes current policies as of the end of 2023) shown in Figure 12 (data from [271]), in 2030, the total capacity is projected to reach 1,516 GW, and it is expected to rise to 2,172 GW by 2050. At the same time, the coal plant capacity in operation is forecasted to be 102 GW in 2030, and it is anticipated to decrease to 69.8 GW by 2050. Additionally, the renewable source capacity in operation is estimated to be 728 GW in 2030, and it is set to increase to 1,162 GW by 2050. It has trends that a significant portion

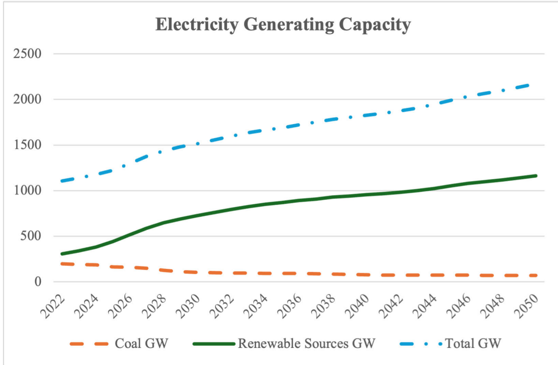

FIGURE 12. Electricity capacity: coal (orange-dashed line), renewable Sources (green-solid line), total (blue-dashed-dotted line).

of coal power plants is expected to be retired, which is also mentioned in [272]. The transition from coal to renewable energy sources is inevitable. However, the modern electrical grid is becoming increasingly complex due to the growing number of asynchronously connected RESs. Consequently, a modern grid necessitates modern infrastructure, such as new devices powered by digital technology or updated pathways for electricity to flow [273].

At first, it is essential to seek opportunities for technological innovations that can improve the efficiency and capacity of RESs. Technological advancements can also lower the cost of RESs, making them more accessible and competitive in the energy market. For example, HVDC technology is one of the potential solutions to efficiently integrate more offshore wind power into the grid. The Dogger Bank wind farm, located in the UK North Sea, is the largest offshore wind farm. It is being constructed in three phases, referred to as A, B, and C, each with a capacity of 1.2 GW [274]. The project utilizes the latest HVDC technology to convert AC power from 95 offshore wind turbines into DC power, which is then transmitted 130 km to an onshore converter station. In addition, TenneT has initiated a program to develop a new 2 GW offshore platform standard and a new Â±525 kV bipolar cable system to maximize the capacity while minimizing the environmental impact of offshore wind connection [275]. Sunrise Wind received its Record of Decision (RoD) from the US Department of the Interior's Bureau of Ocean Energy Management (BOEM) [276]. It is expected to become the largest offshore wind farm in the US once completed. The wind projects are expected to expedite the decarbonization of the world's industrial sectors and open up new economic opportunities. Overall, the integration of cutting-edge technology into renewable energy systems is essential for achieving a cleaner and more sustainable energy future.

Technological innovations in energy storage could promote energy storage technologies in multiple grid applications, such as generation, transmission, and distribution, which could enhance the efficiency of the grid and reduce costs for all customers [277]. These innovations can help to optimize energy production, storage, and distribution, ultimately leading to a more sustainable and reliable energy infrastructure. The Minnesota Public Utilities Commission has given the green light to Xcel Energy's proposal to phase out all of its coal-powered generators and investigate opportunities for integrating new technologies. The company aims to incorporate 600 megawatts of battery energy storage by 2030, capitalizing on anticipated advancements in battery technology [278].

In addition to energy storage, grid-enhancing technologies, such as dynamic line rating management systems, advanced power flow control, and topology optimization, can enhance the grid by increasing the capacity, efficiency, reliability, and safety of existing power lines [279]. These technologies have the potential to transform the operation of the grid and enable a reliable energy transition at a minimal cost. Moreover, these new technologies can be expected to allow more new RESs to be integrated, provide more energy production cost-saving, and create more local construction jobs [280].

Implementing systems that utilize data from across the grid to enhance stability and reliability would be essential for enabling utilities to establish a stable, reliable, and environmentally friendly power system. For example, GE's advanced WAMPAC solutions utilize data from various points across the grid to deliver fast & reliable actions and accurate information [281], which are useful for ensuring grid stability. By incorporating real-time data from across the grid, utilities can make informed decisions and take swift actions to maintain the stability and reliability of the grid.

Based on the latest implementations of control methodologies in the industrial fields, new opportunities for the advanced control theory also emerged. Decolonization, digitization, and decentralization are the three main drivers of power systems evolution worldwide [282]. The advanced control theories focused on by us in this paper are critical in supporting different policy goals in smart grids, as it is inherently related to new technologies and intelligent energy management through the entire value chain from the generation to the consumers [283]. It is noteworthy that, the advanced grid control methods are the heart of the power system evolution especially in industry 4.0, the main impacts of digitized renewable energy systems are addressed in [284] for a case study in Germany. Considering the rapid promotion of energy transition, the environmental concerns, fossil fuel problems, energy system security, and economic and operation cost issues all raise the requirements of suitable control schemes [285]. In the frequency control domain, the reduced inertia due to the increasing installment capacity of RES causes many problems for ISO such as increasing the frequency nadir (maximum frequency deviation) and making the system oscillatory. On the other hand, increasing the power imbalance in the short-term operation results directly in increasing the frequency oscillations. In the future, we are encouraged to develop the following aspects: Increasing the robustness of control methods applied to frequency control schemes; proposing optimal-robust-reliable control methods for frequency control using stochastic distribution control concept [286] that can lead to a new generation of transmission system control in response to increased penetration of renewable generations, and proposing new control methods to make use of WAMPAC, etc.

For the voltage control, it is necessary to consider both static and dynamic stability factors when designing coordination methods. However, the conventional transmission grid voltage stability assessment is inaccurate in predicting the long-term (or static) voltage stability margin of an integrated system, as demonstrated in [287]. A distributed algorithm is proposed in [288] to accurately evaluate the static voltage stability of an integrated system, which conforms to the distributed architecture of coordinated voltage control methods. Although many distributed coordination methods have been proposed, they need to be further tested. Also, most work does not consider the electricity market when designing coordinated voltage control. Since in some systems only a few voltage regulation devices are owned by TSOs, the price mechanisms of dispatching Var resources should be considered in the future.

In summary, the modernization of the grid infrastructure and the integration of cutting-edge digital technologies are essential for ensuring that the grid can effectively integrate a growing number of RESs and enhance its overall resilience and efficiency.

VI. CONCLUSION

The integration of various grid-enhancing technologies is crucial for addressing the current challenges faced in controlling transmission grids. This includes ensuring grid stability amidst growing variability, which requires innovative solutions such as advanced grid monitoring and control systems, energy storage technologies, and flexible grid infrastructure. These technologies have played a key role in balancing the intermittent nature of RESs and ensuring a stable and reliable supply of electricity. This paper offers a comprehensive review of grid-enhancing technologies, providing insights that bridge technical and market perspectives into a cohesive whole. It also highlights various existing industrial projects that address current challenges and enhance the functionality, reliability, and sustainability of transmission grids. Additionally, it discusses some future opportunities for improving transmission grids, emphasizing the ongoing advancements and potential for further enhancements in grid technology.

ACKNOWLEDGMENT

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