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A Comprehensive Study of Various Multi-Area Hybrid Power Systems for Generation Control

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Abstract

This paper is a detailed examination of multi-area hybrid power systems in the control of the generation, taking into consideration the two areas up to five areas connected. As renewable energy sources are increasingly integrated, and modern grids become increasingly complex, the stability of the system itself and the frequency regulation have risen to a major issue. The study highlights the significance of automatic generation control (AGC) and load frequency control (LFC) in the process of integrated functionality of the various energy sources, which include thermal, hydro, gas, solar, wind, and energy storage facilities (ESS). Comparison of evaluations of a 2-area, 3-area, 4-area, and 5-area models shows the gradual increase in complexity of the system, the tie-line interaction, and communication requirements. The paper further demonstrates how traditional PID-based controllers have been replaced with intelligent and decentralized AGC mechanisms, which combine optimization and artificial intelligence-based methods to improve dynamic performance. Findings suggest that, even though five-area hybrid systems are highly efficient and resilient, they need strong control frameworks and complex monitoring systems to deal with the nonlinearities and the uncertainties that are caused by renewable penetration. The results offer compelling information on how to design and optimize the smart, adaptive, and sustainable future power grids in a multi-area hybrid structure.

Keywords: Frequency control, multi-Area hybrid power system, renewable energy integration, intelligent control, load frequency stability, optimization techniques

INTRODUCTION

The rapid development of contemporary power systems has been marked by the increasing incorporation of renewable and nonconventional sources of energy into existing grids. Hybrid power systems, which integrate traditional units of generation, including thermal, hydro, and renewable resources, such as wind, solar, and biomass, have become a potential source for solving the increasing energy needs and requirements to support environmental sustainability. Nevertheless, with renewable resources, there is variability and intermittency, which are major threats to the frequency stability of multi-area power systems [1–5]. This has necessitated good frequency control to achieve quality power, reliability, and security of grid stability during dynamic operational conditions. In classical power systems with large synchronous generators, frequency control is performed using primary, secondary, and tertiary control. Such classical techniques are based on proportional-integral-derivative (PID) controllers and automatic generation control (AGC) schemes to balance generation and load. Although these traditional methods are useful under stable operating conditions, they are prone to limitations due to the uncertainty and nonlinearity of renewable energy integration. Multi-area hybrid power systems are characterized by geographically dispersed control areas that are linked together with tie lines. The

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coordination of each area with others maintains the frequency in the system and planned tie-line power exchanges, making the control strategy more complicated [6–10].

The frequency control structure in multi-area hybrid power systems with a combination of traditional and renewable energies, including thermal, hydro, wind, solar, and storage, is presented in Figure 1. All the control areas are tied together by means of tie lines, and an overarching controller bank uses twenty various frequency control methods, categorized into classical, optimization-based, advanced, intelligent, and hybrid methods. These controllers communicate through automatic generation control (AGC) and control the frequency and tie-line power flows. The system is subjected to loads and disturbances that affect dynamic performance. Frequency and tie-line deviation feedback signals are continuously observed, which allows the adaptive and robust regulation of a system that maintains a stable system under different conditions. The frequency control techniques that have been proposed and experimented with over the years are quite diverse, with traditional linear controllers to modern intelligent and adaptive approaches. Several classical methods, including PID, proportional integral (PI), and optimum linear quadratic regulator (LQR) controllers, remain the subject of study because they are simple and easy to implement. Nonetheless, they tend to be fine-tuned and not as effective in operating conditions that are highly nonlinear and uncertain. To address these deficiencies, soft computing-based methods, including fuzzy logic control (FLC), adaptive neuro-fuzzy inference system (ANFIS), and artificial neural networks (ANNs), have been proposed. Such techniques offer flexibility, adaptation, and resilience for dealing with the dynamic nature of hybrids. In more recent works, evolutionary optimization algorithms such as the genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE), and grey wolf optimization (GWO) have been combined with conventional controllers to obtain optimal parameter optimization and better dynamic responses. Furthermore, more sophisticated control systems such as model predictive control (MPC), sliding mode control (SMC), and robust H 0 control have been investigated to become more resilient to disturbances and parameter uncertainty. The development of deep learning and reinforcement-learning-based controllers highlights only the increased role of artificial intelligence in contemporary frequency regulation. These methods take advantage of the data-driven learning process to address the complexity of the system in real time. This paper presents an in-depth analysis of twenty frequency control methods used in multi-area hybrid power systems. These techniques are discussed in terms of their control philosophy, performance properties, robustness, and performance in renewable-rich environments. Comparative knowledge is provided to demonstrate the advantages, drawbacks, and usage conditions of the traditional, smart, and hybrid methods. The aim is to offer an integrated perspective of frequency regulation measures, thus informing scientists and professionals to adopt the right methods of ensuring secure, reliable, and sustainable operation of present-day power systems [11–15].

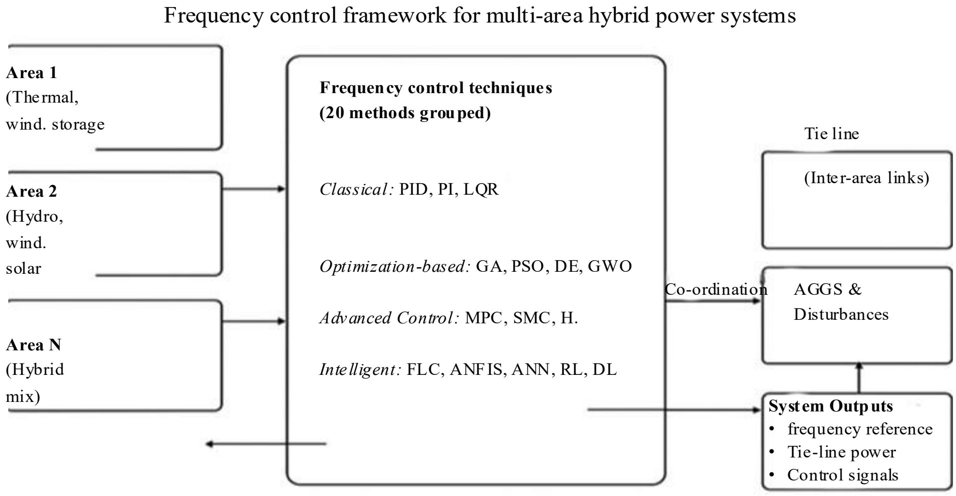

Figure 1. Frequency control framework in multi-area hybrid power systems.

SINGLE-AREA HYBRID SYSTEMS

A single-area hybrid system is a specialized configuration in which diverse energy sources, both conventional and renewable, coexist within a confined geographic or operational boundary. These systems epitomize the growing convergence between conventional generation technologies, such as thermal and hydropower, and renewable sources, such as solar, wind, and energy storage systems, often including batteries and advanced power electronics. Such hybrid systems represent a paradigm shift in the modern energy infrastructure, addressing the critical challenges of reliability, efficiency, and environmental impact. A single-area hybrid system is distinguished by its localized operation, which relies on a limited scope of interconnected components to manage generation, storage, and consumption Figure 2. Unlike multi-area systems, these setups operate in an isolated or minimally interconnected environment. This introduces unique challenges and opportunities, especially in balancing supply and demand while maintaining operational stability. These systems are particularly important in rural, remote, and developing regions, where grid infrastructure may be underdeveloped or absent, making hybrid systems the backbone of decentralized energy solutions. The integration of diverse energy sources within a single-area hybrid system leverages the strengths of the individual components. Conventional power sources, known for their reliability and steady-state generation, provide a stable foundation for this system [16–18].

The essential features and sources of a single-area hybrid system are shown in Figure 3. Energy storage technologies play a crucial role in bridging the gap between intermittent renewable energy generation and continuous load demand. Battery systems, supercapacitors, and flywheels are among the technologies widely integrated into these systems. They serve as buffers, absorbing excess energy during periods of low demand or high generation and releasing it when the system requires additional power. This capability not only enhances the system's reliability but also ensures that fluctuations in generation and consumption do not compromise its stability. The deployment of single-area hybrid systems is often driven by the need to efficiently meet localized energy requirements. For example, these systems can serve as isolated microgrids in rural areas or as backup power solutions for urban centers. However, this is often accompanied by environmental and economic concerns, particularly in the context of fossil fuels. The inclusion of renewable energy sources such as photovoltaic (PV) panels and wind turbines addresses these concerns by offering sustainable and cost-effective alternatives. However, the intermittency and variability of renewables pose operational challenges that hybrid systems must address through intelligent designs and advanced control strategies. The inherent scalability and flexibility of such systems make them suitable for diverse applications ranging from small-scale residential installations to large-scale industrial setups. This versatility ensures their viability across various economic and environmental conditions, enabling them to address energy demands in unique and challenging settings. One of the most critical challenges in single-area hybrid systems is effective coordination and control of diverse energy resources [19–21].

MATLAB Simulink model of a single-area hybrid system for energy generation and load management. Each component of the system operates under distinct dynamics and constraints, making it essential to develop robust control strategies. Advanced algorithms, including optimization techniques, machine learning, and artificial intelligence, have emerged as valuable tools for managing the interplay between generation, storage, and consumption. These algorithms enable predictive decision making, real-time monitoring, and adaptive responses to changing conditions, ensuring that the system always operates efficiently and reliably. Economic optimization is another significant aspect of single-area hybrid systems. The integration of multiple energy sources, each with distinct cost structures, requires a comprehensive economic model to minimize operational costs while maximizing system efficiency. Hybrid systems often employ algorithms to determine optimal dispatch strategies, factoring in variables such as fuel costs, renewable energy availability, and storage dynamics. These strategies not only reduce reliance on conventional generation but also enhance the cost-effectiveness of renewables, making them more competitive with traditional energy sources. The implementation of single-area hybrid systems also involves addressing technical and regulatory challenges. From a

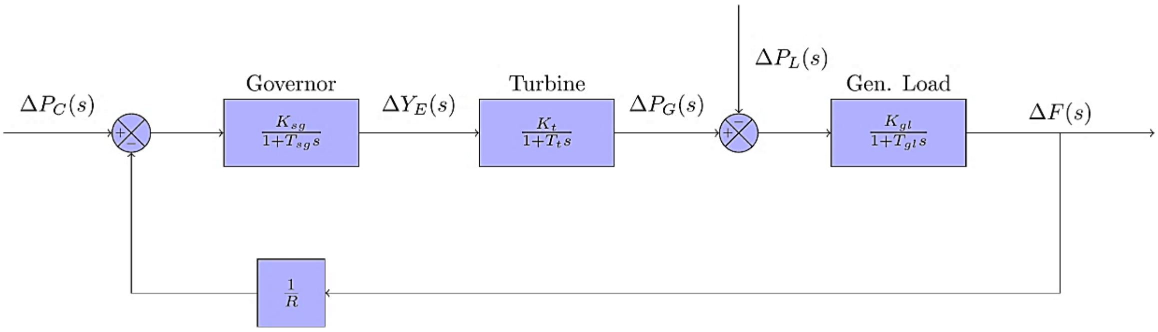

Figure 2. Single-area hybrid system.

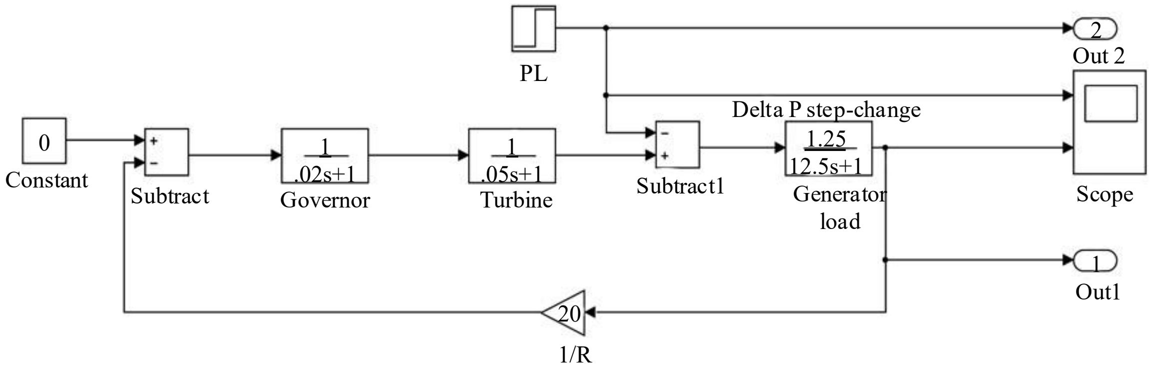

Figure 3. MATLAB Simulink model of a single-area hybrid system.

technical perspective, the design of reliable interfaces between diverse components such as PV inverters, wind turbines, and energy storage units requires high precision and compatibility. Furthermore, the need for seamless communication between distributed energy resources (DERs) and centralized control systems has spurred advancements in communication protocols and data-management techniques. Regulators play an essential role in providing the legal and policy frameworks necessary to enable the development and operation of hybrid systems. Clear policies on grid interconnection, energy pricing, and emissions standards ensure that hybrid systems thrive in a sustainable and economically viable manner. Environmental sustainability is a driving factor for the adoption of single-area hybrid systems. By combining renewable and conventional energy sources, these systems significantly reduce greenhouse gas emissions and environmental degradation [22–25].

TWO-AREA HYBRID SYSTEMS

Two-area hybrid systems are emerging as a cornerstone in modern power engineering, combining distinct energy sources, such as thermal power plants and wind energy systems, to achieve reliable, efficient, and sustainable power generation. These systems are specifically designed to integrate diverse energy sources located across two interconnected regions or areas, each contributing unique characteristics to enhance the overall system performance. The combination of thermal and wind power offers numerous advantages, including leveraging the dispatchable nature of thermal power plants with the variable, yet sustainable, output of wind energy systems. This hybrid approach can mitigate the limitations of standalone systems and provide a pathway for efficient resource utilization and grid stability.

Figure 4 shows a block diagram of a two-area hybrid power system, illustrating the interconnected control and energy flow between two geographically distinct regions integrated with diverse energy generation resources. Each area typically consists of renewable energy sources, such as thermal and wind turbines, supported by conventional generators and energy storage systems, such as batteries, and interlinked by AC/DC buses. The control strategy incorporates droop control for frequency and voltage stability, ensuring load sharing and minimizing interarea power oscillations. The integration of energy management systems optimizes the dispatch of available energy, enabling seamless coordination between areas for stable and efficient operation under varying load demands and generation conditions. The transmission lines connecting these two areas are equipped with smart-grid technologies to facilitate bidirectional power flow, grid frequency control, and system monitoring. Such interconnected setups enable load sharing, reduce dependency on single energy sources, and contribute to improved grid stability, particularly during peak demand periods. Managing energy dynamics in two-area hybrid systems involves a sophisticated interplay of power generation, load balancing, and energy storage mechanisms. The fluctuating output of wind power requires robust forecasting algorithms and real-time data analytics to predict wind patterns and align the generation schedules. Thermal power plants, which are dispatchable, complement wind generation by ramping up or down to offset variability. Coordinated control systems use load frequency control (LFC) techniques to maintain a steady grid frequency and inter-area tie-line power flow. Energy management in this hybrid system often employs optimization algorithms to minimize costs and emissions while ensuring reliability. For instance, during periods of high wind energy generation, thermal plants can operate at a reduced capacity to save fuel and reduce emissions. Conversely, under low-wind conditions, thermal plants can take on the primary load to ensure an uninterrupted power supply. Modern control systems incorporate artificial intelligence (AI) and machine learning (ML) techniques for dynamic energy dispatch, enhancing the overall efficiency and resilience of the system [26–30].

The block diagram in Figure 5 depicts a two-area hybrid power system consisting of thermal and wind power generation units integrated to manage the system's load requirements through an automatic generation control (AGC) mechanism. Each area features a combination of thermal generators and wind

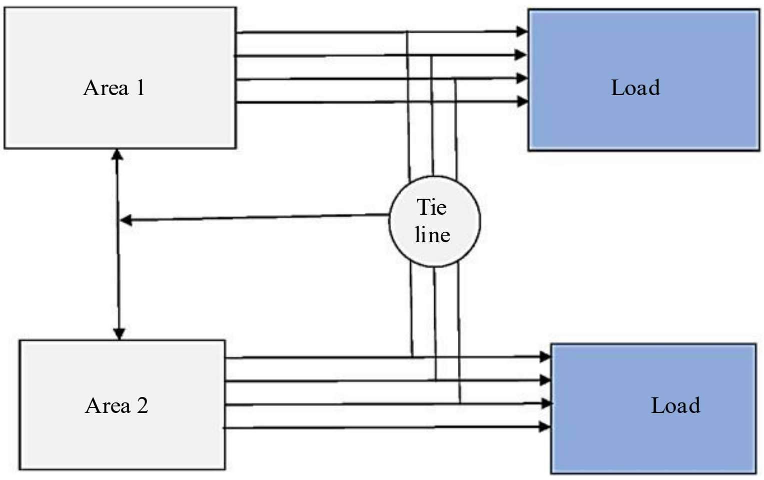

Figure 4. Block diagram of a two-area hybrid system.

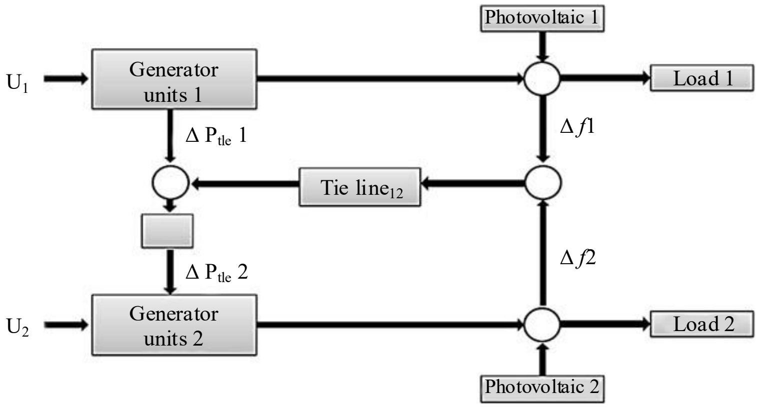

Figure 5. Block diagram of generator units and loads of a two-area hybrid system.

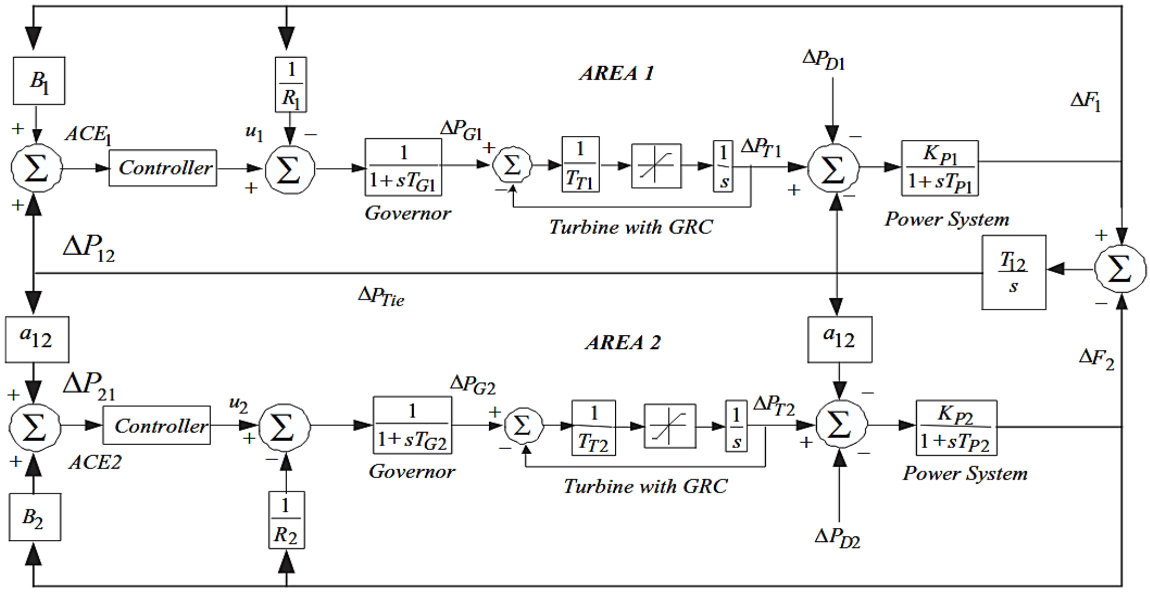

Figure 6. Block diagram of a two-area hybrid power system.

turbines interconnected via tie lines to facilitate the power exchange. The system was designed to maintain frequency stability and power balance across areas under various loading conditions and renewable energy intermittencies. In Area 1, thermal generators provide a stable and controllable base load, whereas wind turbines supply intermittent renewable energy. The AGC in this area continuously monitors the system frequency and adjusts the power output of the thermal units to compensate for the fluctuations caused by wind generation variability. Similarly, in Area 2, the AGC regulates the combined output of its thermal and wind units, ensuring that the total generation meets the local demand while maintaining a predefined tie-line power flow with Area 1. The inter-area tie line serves as a critical link that enables the exchange of excess power between the two areas, enhancing system reliability and operational flexibility. The AGC ensures coordinated control of both areas, maintaining overall frequency stability and minimizing tie-line power deviations. This setup ensures an efficient and balanced energy flow, optimally utilizing the available generation resources, while addressing the challenges associated with integrating renewable wind energy into the grid [31–34].

Figure 6 shows a two-area hybrid power system designed to manage energy flows and ensure stable operation using an integral proportional-integral-derivative-fractional (IPIDF) controller. This hybrid system comprises two interconnected areas, each containing thermal power generators, renewable energy sources such as wind turbines, and energy storage systems. The areas are connected by a tie line to facilitate power exchange and promote system stability, reliability, and efficient resource utilization. In the model, each area included thermal generators for base-load power, wind energy units to integrate intermittent renewable energy, and battery storage systems to buffer fluctuations. The subsystems within each area were designed in Simulink using standard block libraries for power sources, storage, load, and control units. The tie line dynamically links the two areas, with blocks representing the power flow and stability maintenance. The model also incorporated detailed load models to simulate realistic demand variations over time. The IPIDF controller is central to the system operation, offering advanced control capabilities by leveraging fractional-order calculus for precise regulation. This controller integrates the benefits of traditional proportional, integral, and derivative actions, while adding fractional-order flexibility to fine-tune the response. In this hybrid system, the IPIDF controller adjusts the power outputs of thermal generators and energy storage units in real time to maintain frequency stability and balance loads and ensure seamless coordination between renewable energy generation and demand. The Simulink model simulates various operational scenarios, including changes in the load, wind speed variability, and tie-line disturbances. The IPIDF controller reacts dynamically by redistributing power generation across the two areas, maintaining the nominal frequency, and ensuring minimal tie-line power deviations. It also mitigates the effects of wind power intermittency and sudden load changes, demonstrating robust system performance, even under challenging conditions. By incorporating the IPIDF controller, the system achieved superior stability, a better dynamic response, and optimized energy utilization. This model is a powerful tool for researchers and engineers to study and enhance hybrid power systems, offering insights into control strategies that can be applied to large-scale grid applications integrating renewable energy [35].

THREE-AREA HYBRID SYSTEMS

The increasing demand for sustainable and reliable energy has accelerated the integration of renewable energy resources into the existing power grids. Hybrid power systems, which combine conventional generation units with renewable sources, such as solar, wind, hydro, and biomass, have become a vital solution for achieving energy efficiency and environmental sustainability. Among these, three-area hybrid systems play a crucial role in large-scale interconnected power networks, where different geographical regions or "areas" are linked via tie lines to collectively share generation and load responsibilities. Each area typically incorporates a unique mix of energy sources and load demands, making coordination and frequency regulation significant challenges. Stability and frequency control are critical in a three-area hybrid power system for ensuring seamless operation across interconnected networks. Each area may have varying levels of renewable energy penetration, leading to nonlinearity, intermittency, and unpredictable fluctuations in the power output. For example, an area with a high solar capacity is vulnerable to irradiance changes, whereas an area dominated by wind power may face sudden variations in wind speed. When such fluctuations occur, they cause deviations in the system frequency, not only within the local area, but also across interconnected areas through tie-line power exchanges.

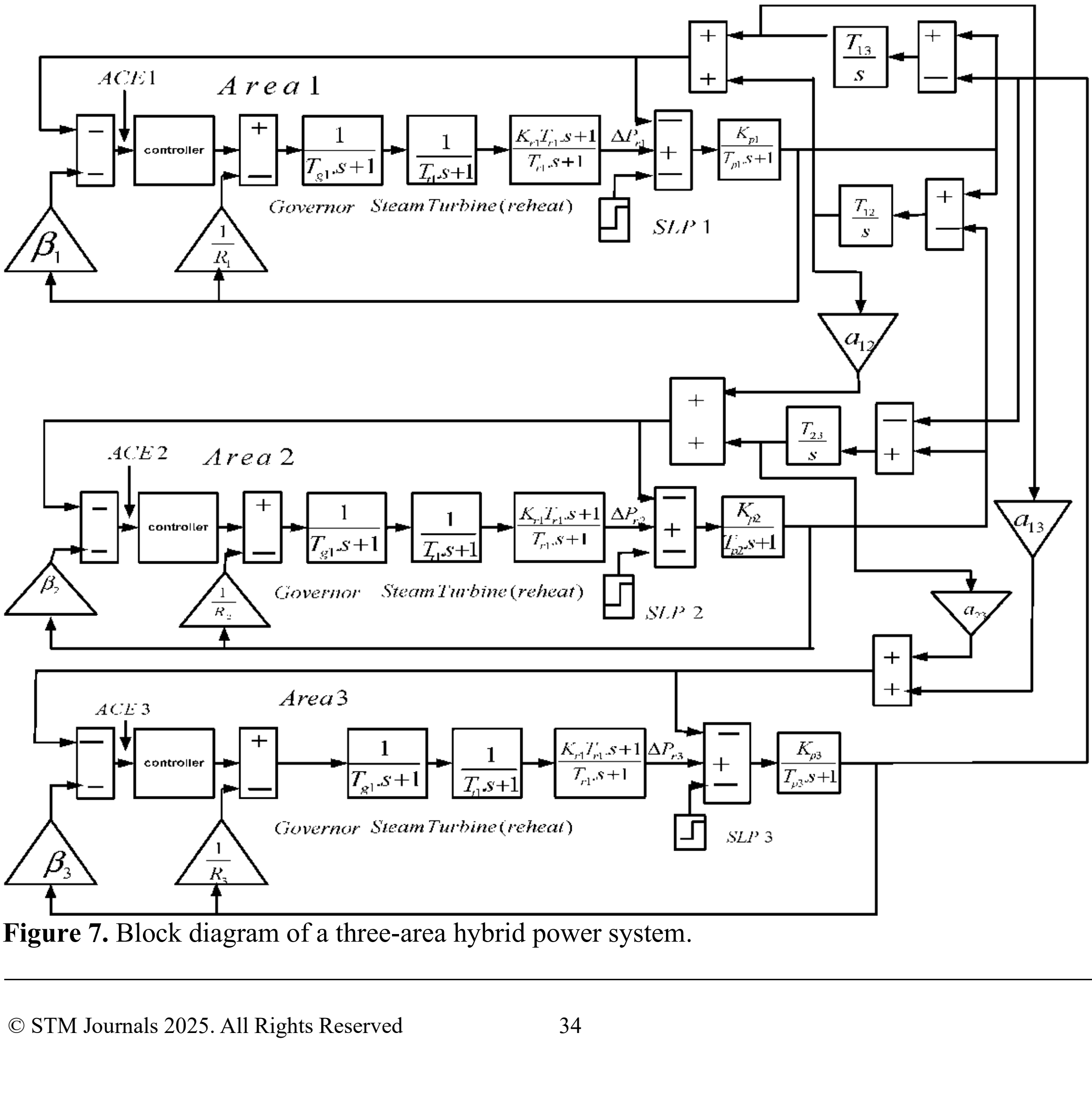

Figure 7. Block diagram of a three-area hybrid power system.

Figure 7 depicts a three-area hybrid power system, where each area integrates different generation units, such as thermal, hydro, wind, or diesel units, interconnected through tie lines. Each control area has its own controller that regulates the frequency deviations and tie-line power errors using automatic generation control (AGC). Nonlinearities, such as generation rate constraints (GRC) and boiler dynamics, are included for realistic modeling. The tie lines facilitate coordinated power exchange, ensuring a system balance during load fluctuations or renewable intermittency. This structure highlights the interdependence of areas and the role of AGC in maintaining frequency stability and secure operation across the hybrid grid. To maintain reliable operation, the frequency control mechanisms must be coordinated across all three areas. Conventional automatic generation control (AGC) schemes often form a baseline for managing frequency deviations and scheduled tie-line power flow. However, the dynamic complexities introduced by renewable integration necessitate advanced strategies, such as model predictive control, adaptive control techniques, and intelligent methods, such as fuzzy logic, artificial neural networks, and reinforcement learning. These approaches enable the system to respond quickly to disturbances, adapt to changing system dynamics, and maintain stability under varying operating conditions. The significance of studying three-area hybrid systems lies in their ability to simulate real-world multi-area power networks, where interdependence between regions is a norm. They provided an effective framework for analyzing how different frequency control techniques are performed under renewable-rich conditions. Moreover, by exploring multiple strategies ranging from classical PI/PID controllers to optimization-based and intelligent hybrid approaches, researchers can identify the most efficient solutions for enhancing frequency stability. Thus, three-area hybrid systems serve as a crucial testbed for designing resilient and adaptive frequency control frameworks that can be extended to larger and more complex power grids in the future [36].

FOUR-AREA HYBRID SYSTEMS

The modern power sector is undergoing a paradigm shift driven by the integration of renewable energy resources, advancements in control technologies, and growing demand for reliable, sustainable, and efficient electricity. Hybrid power systems, which incorporate conventional generation units, such as thermal and hydro, with renewable sources, including wind, solar, and biomass, have emerged as a promising solution to meet global energy needs while mitigating environmental challenges. In this context, four-area hybrid power systems are an advanced extension of multi-area networks designed to represent complex real-world grid interconnections where multiple geographically distributed areas interact dynamically. A four-area hybrid system typically comprises four distinct control areas, each comprising its own mix of generation resources, storage technologies, and load demands. These areas are interconnected through tie lines, which enable power exchange and operational coordination. For instance, one area may primarily depend on thermal and hydro units, another on wind and solar units, while others integrate a combination of biomass, storage, and conventional plants. The diversity in resource availability and demand profiles creates interdependence that enhances efficiency but also complicates system operation. Sudden fluctuations in renewable generation or variations in load demand in one area can propagate disturbances across all interconnected regions, leading to deviations in the frequency and tie-line power flow. Maintaining the frequency stability in interconnected networks is a primary challenge. The four-area configuration in Figure 8 introduces additional layers of complexity compared with two- or three-area systems. The presence of multiple tie lines and diverse generation portfolios results in nonlinearity, higher-order dynamics, and increased uncertainty. Conventional frequency control strategies, such as automatic generation control (AGC) using PI or PID controllers, are effective for small-scale and less-variable systems and often fail to handle the stochastic nature of renewable-rich four-area networks. Consequently, advanced frequency regulation strategies are necessary to ensure reliable and secure operations.

Over the years, various control methods have been proposed and implemented for four-area hybrid systems. Optimization-based strategies such as genetic algorithms (GA), particle swarm optimization (PSO), and differential evolution (DE) have been employed to fine-tune controller parameters and improve dynamic responses. Advanced robust methods, such as model predictive control (MPC),

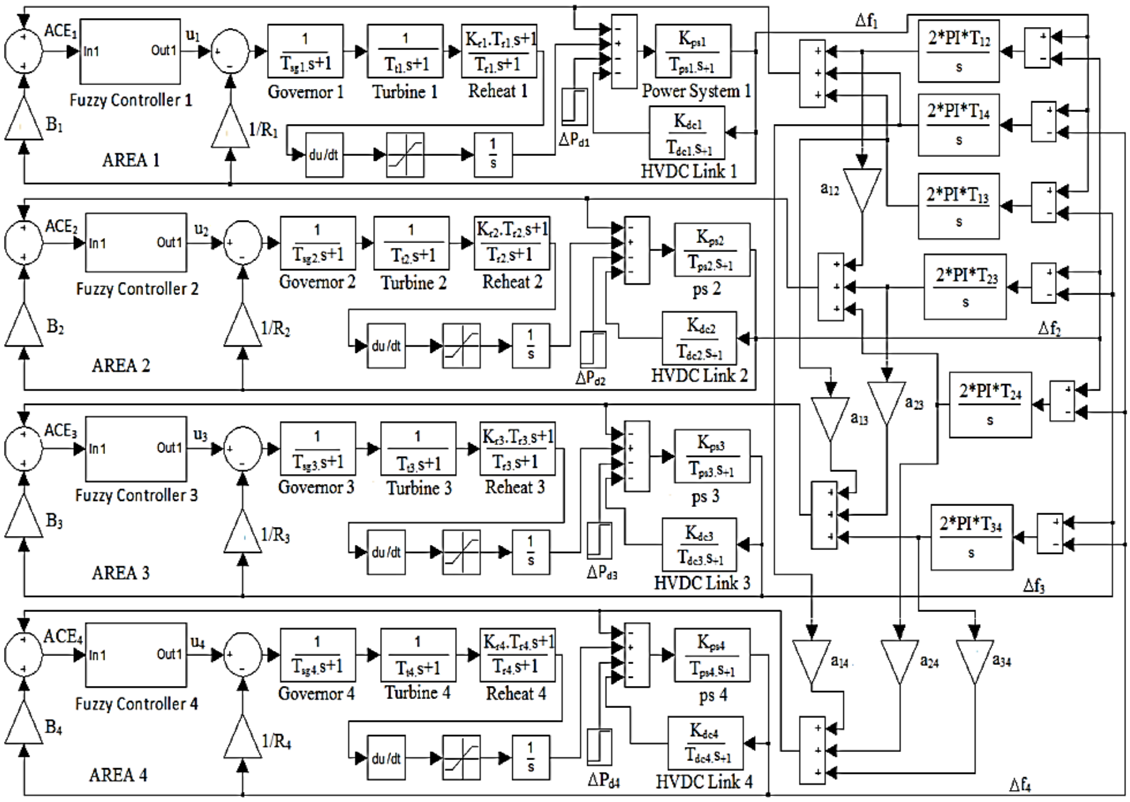

Figure 8. Block diagram of a four-area hybrid power system.

sliding mode control (SMC), and H∞ control, provide resilience against uncertainties and system disturbances. Furthermore, intelligent techniques, including fuzzy logic controllers (FLC), adaptive neuro-fuzzy inference systems (ANFIS), artificial neural networks (ANN), and reinforcement learning (RL), offer adaptability and learning capabilities to manage the complex time-varying behavior of hybrid power systems. Hybrid approaches that integrate classical, optimization, and intelligent techniques are increasingly being recognized for their superior performance. The study of four-area hybrid systems is important because they closely resemble large-scale real-world power networks. With increasing renewable energy penetration, the ability to manage frequency and tie-line stability across multiple interconnected areas is crucial for ensuring uninterrupted supply, grid resilience, and power quality. Moreover, the four-area models provide an effective testbed for comparing and validating different frequency control strategies under realistic conditions. By exploring a range of conventional, optimization-based, and intelligent controllers in such systems, researchers can develop robust frameworks that enhance the adaptability and stability of future smart grids [37].

FIVE-AREA HYBRID SYSTEMS

Modern power network transformation is also motivated by the pressing necessity to incorporate renewable energy resources in addition to traditional generation so that power networks can be sustained, reliable, and secure in terms of energy. Hybrid power trees, whereby traditional sources, that is, thermal, hydro, and nuclear power, are combined with renewable ones, such as wind, solar, and biomass, have become an important system to consider when it comes to increasing global electricity demand and lowering carbon emission levels. In this respect, five-area hybrid power systems are a more developed form of network connectivity, which provides realistic test conditions for studying frequency regulation, load sharing, and system stability in multi-regional grids. A five-area hybrid power system is a five-linked system in which the areas have various generation mixes, energy-storage hardware, and load patterns. For example, a region can mainly use thermal and solar energy; some can use hydro and wind power, while others can use biomass energy, geothermal energy, and storage. These regions are connected through tie lines, which allow them to exchange power and use resources in a coordinated manner. It offers both benefits (enhanced reliability and resource sharing) and disadvantages (disturbances in one region, e.g., load variations, renewable intermittency, or faults) and is rapidly propagated across the entire network because of the interconnection. The errors in the system frequency and tie-line power flows that arise demand advanced control procedures to ensure stability. A five-area system has a much higher level of dynamics than two-, three-, or four-area systems because of the higher number of tie lines, richer interaction between areas, and interdependency of areas. The areas should control their local frequency and generation and provide scheduled power exchanges with other areas. The combination of high percentages of renewable energy also makes control more difficult because it is intermittent and unpredictable. For example, abrupt changes in solar irradiance or wind speed can cause one region to become unstable, thus affecting other regions that are interconnected. There is also renewable frequency biasing (RFB units) to consider the stochastic renewable contribution. The tie lines between the five areas facilitate power exchange between regions, and each tie line is modeled as a transfer function to represent the synchronization of power coefficients and time constants. These tie lines ensure that perturbations in one region, such as load variations or renewable intermittency, influence the dynamics of all interconnected regions. To compensate for variations of this nature, AGC reduces the Area Control Error (ACE) by coordinating the generation of all units, which restores the nominal frequency and scheduled tie-line flows. This five-area AGC model is notable because it represents the nonlinearities, uncertainties, and interdependencies of the large-scale hybrid grids. It is a multipurpose testbed that is utilized to test the practices of conventional, optimization-based, and intelligent control strategies in their complex operating conditions. This implies that frequency management in five-area hybrid systems requires sophisticated coordination and strong strategies. Frequency deviations and tie-line power flows have traditionally been regulated using automatic generation control (AGC) based on proportional integral (PI) or proportional integral derivative (PID) controllers. Although these methods are easy and very popular, they tend to be inadequate when dealing with large multi-area networks with a large portion of renewable sources. To overcome these shortcomings, scholars have suggested optimization-based methods, such as genetic algorithms (GA), particle swarm optimization (PSO), differential evolution (DE), and grey wolf optimization (GWO), to optimize controller gains on a smaller scale. More sophisticated techniques, such as model predictive control (MPC), sliding mode control (SMC), and robust H + control, increase resilience to nonlinearities and parameter uncertainties. Fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), artificial neural networks (ANN), reinforcement learning (RL), and deep learning (DL) are intelligent methods that provide both flexibility and data-based learning and are thus especially effective when dealing with dynamic and uncertain environments. The idea of hybrid strategies combining classical, optimization, and intelligent controllers is becoming one of the most effective ways to achieve stability and flexibility in complex grids. The importance of this study on five-area hybrid power systems is that they are more or less representative of the form of large-scale interconnected grids that are practiced, such as inter-regional or national networks. This makes it possible to test and compare various control strategies, detect trade-offs, and create strong frameworks to regulate frequencies, as it is a complete testbed and allows researchers to evaluate and compare the effectiveness of various control strategies. Finally, the experience of five-area systems can be used to inform the design of resilient, efficient, and adaptive smart grids that can support the needs of a renewable-driven future [38].

Figure 9 illustrates the detailed structure of a five-area hybrid power system integrated with automatic generation control (AGC) for frequency regulation and tie-line power flow management. Each control area (B1–B5) represents a distinct hybrid power source: Area 1 combines thermal and hydro units, Area 2 incorporates hydro and wind generation, Area 3 integrates thermal and diesel units, Area 4 combines thermal and gas units, and Area 5 links thermal with nuclear generation. The diversity of the generation units reflects the hybrid nature of the system and its ability to simulate real-world grid conditions. Each area was equipped with a controller that generated a control signal based on local frequency deviations and tie-line power errors. These signals are fed into generation units through components such as governor dead bands (GDB), boiler dynamics, and governor response characteristics (GRC). Nonlinearities, such as generation rate constraints (GRCs) and boiler time constants, are modeled to reflect the practical system limitations [39, 40].

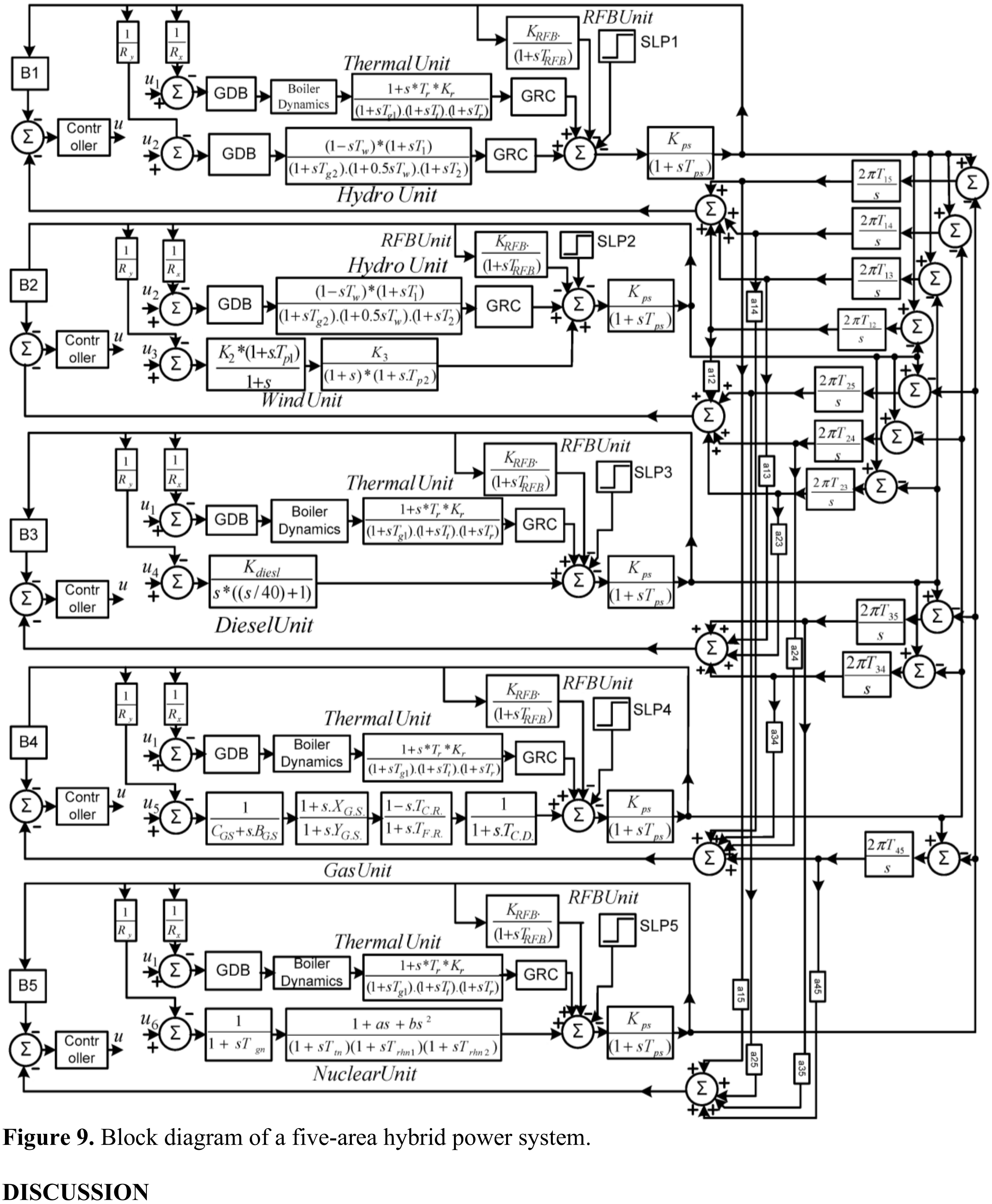

Figure 9. Block diagram of a five-area hybrid power system.

DISCUSSION

The intense development of modern power systems has contributed to the creation of multi-area hybrid energy networks that include numerous traditional and non-traditional sources of power generation. These interconnected systems aim to increase the reliability, stability, and efficiency of operations, while also addressing energy requirements and environmental issues. Multi-area hybrid power systems are often defined as systems comprising two or more control areas, each having its own generation units and load centers that, using tie lines, can be coordinated to operate jointly and share power. More interconnection of areas increases the complexity of the system's functioning. A two-area system is the least complex configuration used to investigate the fundamental inter-area load frequency control (LFC) and tie-line power exchange. The dynamics increase in a nonlinear and challenging manner depending on the number of interconnections, communication dependencies, and availability of various energy resources, including thermal, hydro, gas, solar, wind, and energy storage systems, as the network increases to three, four, and five areas. System frequency and scheduled tie-line power flow are also key activities in large-scale systems under varying renewable generation and load conditions. Automatic generation control (AGC) is important for controlling these complexities. AGC constantly tracks system frequency deviations and tie-line power imbalances, and in real time, modulates the output of the participating generating units to get the system back on track. AGC coordination can be extremely complex in a five-area hybrid power system and requires decentralized or intelligent control, possibly aided by artificial intelligence (AI) or optimization algorithms to achieve greater adaptability. Therefore, the analysis of the performance and interaction of multi-area hybrid systems, from two to five areas, can be a valuable contribution to understanding the difficulties associated with the control of frequency, generation dispatch optimization, and resilient operation of the grid in smart energy networks in the future.

The comparison in Table 1 shows that there has been a gradual escalation of complexity, coordination, and control requirements as the power system transforms into a 5-area design, in contrast to the 2-area design. The interconnection is also easy in a 2-area system with only one tie line and very little communication, which is suitable for small regional networks. The 3-area system presents additional tie-lines and coordination problems and demands moderate communication and multi-loop control systems to balance the frequency and tie-line power. The 4-area system contains a tremendous number of tie-lines and dynamic interactions and requires sophisticated control techniques, such as hierarchical or distributed AGC, and better communication infrastructure. The vibrations and frequency variations of the system increase and require strong damping and optimization methods. A 5-area hybrid

Table 1. Comparison of multi-area systems.

S.N.	Parameter	2-area system	3-area system	4-area system	5-area system
1.	System Complexity	Simple interconnection; easy to model and simulate	Moderate complexity with additional tie-line dynamics	High interconnection complexity	Very high complexity; multiple cross-coupled interactions
2.	Number of Tie-Lines	1 tie-line	3 tie-lines	6 tie-lines	10 tie-lines
3.	Control Coordination	Bilateral coordination	Tri-lateral coordination with shared balancing	Multi-lateral coordination required	Fully decentralized with cooperative coordination algorithms
4.	Generation Mix	Typically, thermal hydro	Thermal–hydro–gas	Hybrid with inclusion of renewables	Comprehensive mix: thermal, hydro, gas, solar, wind, storage
5.	Frequency Stability	High stability, less oscillatory	Moderate oscillations under disturbances	Increased oscillations; needs advanced damping	Highly oscillatory, requires robust control and predictive tuning
6.	AGC Structure	Simple PI or PID controllers	Multi-loop PID/fuzzy controllers	Hierarchical or distributed AGC	Decentralized, intelligent, and AI-assisted AGC mechanisms
7.	Tie-Line Power Control	Single inter-area power exchange	Multiple pairwise exchanges	Dynamic multi-path power flow	Complex tie-line management using optimization and communication networks
8.	Communication Requirement	Minimal communication between the two areas	Moderate; inter-area data sharing	High; needs synchronized data exchange	Very high; employs wide area monitoring systems (WAMS) and SCADA
9.	Control Objectives	Maintain frequency and tie-line schedule	Maintain balance among the 3 regions	Optimize frequency, cost, and reliability	Achieve dynamic stability, optimal dispatch, and renewable integration
10.	Application Scope	Suitable for small regional grids	Medium-sized regional systems	National-level interconnected grids	Continental or large-scale smart grids with hybrid and distributed generation

system is highly complicated, with a variety of sources, such as thermal, hydro, gas, solar, wind, and energy storage. Ten-tie line coordination will demand decentralized or AI-based mechanisms of AGC, backed up by wide-area monitoring systems (WAMS) and real-time data interchange. The present setup is indicative of large-scale national or continental smart grids, in which frequency stability, reduced inter-area oscillation, and power contracting are of paramount importance. Overall, the table highlights the fact that higher-area systems require smarter, adaptive, and communication-based control strategies to guarantee safe and effective operation of the grid.

CONCLUSION

A comparison of different multi-area hybrid power systems shows that the complexity of systems, communication requirements, and control issues increases exponentially with the expanded number of areas related to one another. Although two-area systems can be used to achieve simple frequency control, three- and four-area systems provide more in-depth information about inter-area oscillations, coordination, and renewable integration. In the five-area hybrid configuration, an ideal model of contemporary large-scale power networks, coordinated AGC strategies, and intelligent control algorithms are crucial for maintaining stability, reliability, and efficiency. In this regard, advanced control methods, including fuzzy logic, neural networks, model predictive control (MPC), and metaheuristic optimization, are required to yield a fast dynamic response and a reduction in frequency deviations within several regions. In addition, the integration of energy storage and wide area monitoring systems (WAMS) can make interconnected networks more flexible and resilient. In summary, future smart grid systems are built on multi-area hybrid systems, with automation, decentralization, and renewable coordination at the center of the future to establish sustainable, secure, and high-performance energy systems. Future investigations should focus on AGC frameworks that are cyber-secure, AI-driven, and globally stable while changing renewable and load profiles.

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