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Wind Farms and Flexible Loads Contribution in Automatic Generation Control: An Extensive Review and Simulation

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Abstract: With the increasing integration of wind energy sources into conventional power systems, the demand for reserve power has risen due to associated forecasting errors. Consequently, developing innovative operating strategies for automatic generation control (AGC) has become crucial. These strategies ensure a real-time balance between load and generation while minimizing the reliance on operating reserves from conventional power plant units. Wind farms exhibit a strong interest in participating in AGC operations, especially when AGC is organized into different regulation areas encompassing various generation units. Further, the integration of flexible loads, such as electric vehicles and thermostatically controlled loads, is considered indispensable in modern power systems, which can have the capability to offer ancillary services to the grid through the AGC systems. This study initially presents the fundamental concepts of wind power plants and flexible load units, highlighting their significant contribution to load frequency control (LFC) as an important aspect of AGC. Subsequently, a real-time dynamic dispatch strategy for the AGC model is proposed, integrating reserve power from wind farms and flexible load units. For simulations, a future Pakistan power system model is developed using Dig SILENT Power Factory software (2020 SP3), and the obtained results are presented. The results demonstrate that wind farms and flexible loads can effectively contribute to power-balancing operations. However, given its cost-effectiveness, wind power should be operated at maximum capacity and only be utilized when there is a need to reduce power generation. Additionally, integrating reserves from these sources ensures power system security, reduces dependence on conventional sources, and enhances economic efficiency.

Keywords: wind power plants; flexible load units; automatic generation control; dispatch strategy; forecasting errors; smart power system

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1. Introduction

Renewable energy technologies, such as wind power, have rapidly developed worldwide in the past decade. Despite being connected to different voltage levels of power systems, the power generated by wind power plants largely depends on unpredictable natural factors, such as wind speed. The inherent unpredictability can result in considerable repercussions on the operational functioning of the system, causing deviations from the intended values of generation and power exchanges, ultimately leading to a real-time power deficit between the demand and supply of energy. Power system schedulers employ different scheduling approaches to equilibrate the generation and load demand. However, wind power uncertainty often necessitates supplementary operational reserves from conventional power stations, amplifying operational expenses and carbon dioxide emissions [1,2]. To tackle this problem, it is crucial to harness the potential of wind power to offer system services in active power-balancing operations, similar to conventional power systems. Furthermore, enabling loads to be flexible allows them to actively participate in load-generation balancing, effectively reducing operating costs and carbon emissions and ensuring reliable and secure power system operation.

Frequency deviation in a power system reflects an energy supply-demand discrepancy, posing a risk of destabilizing the system and causing severe damage and outages. To ensure stability, a multi-level control mechanism comprising primary, secondary, and tertiary controls is implemented to regulate the system frequency, with each level functioning on different timescales [3]. The primary control responds automatically to frequency changes, utilizing governors within milliseconds to seconds. The secondary control is called automatic generation control (AGC) [4], which operates on a minute-by-minute basis, monitoring and adjusting power output to regulate the system frequency. In contrast, the tertiary control releases the secondary reserves [5]. This study focuses on the AGC system, which keeps the system balance at a minimum cost by integrating the reserve power from conventional and non-conventional power-generating units [6]. Wind farms with advanced technology and controllability, along with flexible loads such as electric vehicles (EV) and temperature control loads (TCL), can contribute to the AGC system by actively participating in grid ancillary services. Therefore, this research article reviews the participation of wind power and flexible load in AGC service, aiming to reduce the dependency on traditional generating units and increase the economic security of the system's operation.

Wind turbines are being studied as a prospective source for providing ancillary services to maintain grid reliability by controlling their active power output. Frequency regulation, delivered through AGCs, is among these services [7]. Moreover, utilizing wind power in AGC services can result in substantial economic gains by mitigating the dependence on traditional generation resources and curtailing the expenses of ancillary services. Given the immense significance of wind power plants, both the academic and industrial domains have conducted exhaustive research to further improve the ancillary service capacities of wind power plant systems [3,8,9]. In [8], the researchers assessed an 800 kW IEC Type 4 wind turbine located in Regina, SK, Canada, through multiple tests to ascertain its aptitude for regulating the system frequency. The study furnishes technical details on the potentials and constraints of wind turbine technology in offering secondary frequency response service to the grid. The PJM methodology shows 59% and 65% performance scores above and below rated wind speeds, respectively. The research concludes that, despite the low performance score, employing wind power in the regulation market is more lucrative.

The authors in [10,11] provide a comprehensive review on the design, performance, and economic aspects of solar dish/Sterling systems (SDSS) in distributed energy systems. They discuss experimental studies on standalone SDSS plants and explores hybridization options with micro gas turbines and other solar energy systems. The study emphasizes the importance of developing hybrid multi-generation systems to advance dish/Sterling applications and calls for additional efforts to enhance their feasibility. Additionally, the authors propose a novel hybrid prediction model that integrates the CHOA with the RVFL network to accurately forecast the output power of a solar dish/Sterling power plant, improving the reliability of predictions. The regulation of wind power can be further enhanced with sufficient wind power availability and the wind turbine's capability to precisely and rapidly trail the power command signal from AGC [9]. The investigations described above have demonstrated that wind power plants possess the potential to furnish AGC services. Nonetheless, the technical potentialities and restrictions of wind power plants for delivering AGC services hinge on the type of wind turbine technology adopted and the control tactics implemented [12]. Hence, reviewing wind energy technologies and their corresponding control mechanisms is pivotal to offering frequency support services to the grid.

Analogously, non-conventional loads, such as electric vehicles (EVs) and thermostatically controlled loads (TCLs), possess the potential to yield significant benefits for the power grid owing to their dynamic load characteristics, as elaborated in [13]. These loads display pliable consumption patterns and possess energy storage capabilities, rendering them a possible solution for the power grid's challenges. A study executed in Denmark [14] shows that flexible load units (FLUs) are adept at dispensing ancillary services, specifically regulation services (secondary and tertiary), thereby diminishing the operator's burden of forecasting and monitoring the operations of high-wind-power integrated power systems. Further, exploiting these non-conventional loads can reduce the overall system costs by diminishing the production of traditional power plants. In Reference [15], the potential of consumption units to carry out ancillary services by relocating energy for extended hours without jeopardizing their primary role is well documented. In Denmark, the estimation report suggests that 200 MW of cold storage and 75,000 electric vehicles (600 MW) functioned as adaptable consumption units in 2020. The flexibility of these loads enables them to respond to peak hour demands and shift the load to optimize the power flow in existing grids, thus curbing the necessity for reserves and maintaining system stability without extra costs [15,16]. The authors of [15] propose an integrated approach for building space-heating loads into an integrated community energy system to optimize power generation and consumption schedules. The study emphasizes that buildings consume about 40% of global energy, with 50% used for heating and cooling. In recent years, EVs have gained significant attention as a helpful resource for demand response. V2G technology allows EVs to function as battery energy storage systems, enabling a bi-directional power flow with the power system.

Considering the aforementioned advanced technologies, this article has undertaken a comprehensive survey on the considerable role of wind farms and flexible loads in load frequency control, an essential function of AGC. This review encompasses diverse aspects of the contribution, starting with a detailed explanation of the fundamental concepts of wind and flexible load integration in AGC services. Special attention is devoted to the contribution of EVs and TCLs among the flexible loads. A comprehensive review of wind-energy-based AGC systems includes various control strategies, such as soft computing control, model predictive control, intelligent control approaches, and their coordination with other devices, such as flexible AC transmission system (FACTS) devices and energy storage systems. Furthermore, a detailed critical review is conducted on the contribution of EVs in AGC systems, encompassing centralized and distributed control strategies, economic-awareness-based strategies, and control strategies based on soft computing techniques. A detailed literature review on the contribution of TCLs is conducted following this. In the subsequent section, the article proposes a real-time dynamic dispatch strategy for the AGC unit, highlighting the integration of wind power and flexible loads while ensuring power system security. A future Pakistan power system simulation model is developed to evaluate the proposed control strategy, considering a highly windy day in 2022. The simulation outcomes demonstrate that integrating wind power and flexible loads can efficaciously alleviate real-time power imbalances caused by the substantial penetration of wind power, thereby enhancing the power system's security. Moreover, the proposed dispatch strategy ameliorates the system's operational cost by optimizing the utilization of minimum reserves for active power balancing services by operating conventional power plants at their minimum limits. Some of the pertinent contributions of this study are as follows.

- The fundamental principles underlying the integration of wind power into an automatic generation control (AGC) service are explained, with a particular focus on a comprehensive model of a type 4 wind power plant. Likewise, incorporating electric vehicles (EVs) and thermostatically controlled loads (TCLs) into AGC services is elucidated through mathematical equations and integrated models.

- An in-depth review of the involvement of wind power in frequency ancillary services is proffered, encompassing diverse control strategies such as model predictive control, intelligent control, and soft computing techniques, as well as their integration with other devices such as flexible AC transmission systems (FACTS) and energy storage systems.
- A detailed review of integrating electric vehicles (EVs) and temperature control loads (TCL) in the AGC system is presented, focusing on the control strategies based on centralized and decentralized schemes, economic awareness, and soft computing control schemes.
- A real-time dynamic control strategy is developed for the developed AGC system, emphasizing the integration of wind power and flexible loads. The control strategy is implemented in the future Pakistan power system model by considering a highly windy day in 2022.

The paper is organized as follows: Section 2 provides an overview of the fundamental equations pertaining to the contribution of wind power in the AGC system, along with a review of the current state-of-the-art practices. Section 3 focuses on the contribution of flexible loads, electric vehicles (EVs), and thermostatically controlled loads (TCL) in AGC services. Section 4 outlines the proposed AGC model for the power system, encompassing the modelling of generating units. Section 5 concludes the paper.

2. Automatic Generation Control and Wind Power

2.1. System Overview

Research indicates that wind farms have the potential to significantly impact the AGC function by providing frequency regulation services [4]. However, wind turbines differ from conventional power plants in how they control power output. Nonetheless, two techniques can be used to regulate wind turbine power output: blade pitch angle adjustment and rotor speed adjustment. The blade pitch angle technique changes the angle of the wind turbine blades to regulate power output. The turbine's power output can be controlled by adjusting the wind's angle of attack on the blades. This technique is especially beneficial when wind speeds fluctuate across the wind farm and can regulate the power output from each turbine. The rotor speed technique involves altering the rotational speed of the turbine blades to regulate power output. This technique is often utilized when wind speeds are relatively stable across the wind farm and can also control power output from each turbine [6]. These regulatory measures affect the quantity of wind energy extracted and can be utilized to regulate the grid frequency [17,18].

The AGC system is an indispensable power grid component, which is crucial in preserving its stability. Its primary objective is to react promptly to power demand alterations, commencing within seconds and persevering for several minutes. This real-time response is executed by allocating the load change among individual wind turbines (WTs) within a wind farm (WF) to ensure that the system frequency deviation and tie-line power flow deviation are maintained at zero [7]. The AGC set point for each WT generator is established based on a combination of PI controller parameters and participation factors (PFs). This creates a well-calibrated balance of control measures that ensure the system operates smoothly and safely. The process of ascertaining the optimal power factors (PFs) is multifaceted, involving an intricate analysis of various factors. Such factors include the wind turbines' up and down ramp rates (WTs), operating reserves, dispatch limits, and generation costs. A comprehensive evaluation of these factors ensures that optimal PFs are selected and employed in the power system. Failure to do so could adversely affect the power system's efficiency, stability, and reliability. Determining the optimal PFs requires a high degree of skill, expertise, and experience, and a thorough understanding of the complex interaction between various components in the power system [19]. To attain the most efficient frequency assistance from a wind farm, it is crucial to establish a closely coordinated interaction between the two tiers, namely at the level of individual turbines and the power plant. This is facilitated by a set of signals that enable effective communication between the two levels. Figure 1 provides a detailed representation of a wind farm, illustrating the interaction of signals between the levels of a power plant and a turbine [12].

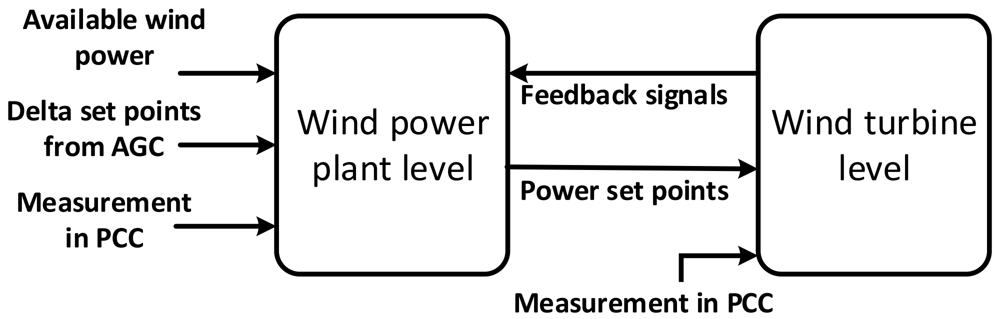

Figure 1. Interaction of signals on WT and WPP levels.

This interaction is characterized by the exchange of power signals and feedback signals, which are influential in delivering the necessary grid support as required. The primary controller block of the wind power plant (WPP) is the main part. It is crucial in setting the reference signal for every wind turbine controller. Determining the reference signal involves multiple inputs, encompassing the existing wind power, AGC set point, grid measure power, and real-time feedback signal of each wind turbine. The feedback signal yields instantaneous data about wind turbine functionality, which is then utilized to establish the reference signal, thereby achieving optimal frequency support [17].

Figure 2 presents a wind farm considering the dynamic features required to provide ancillary services, specifically primary and secondary control through wind turbines' AGC [20]. The wind farm comprises two primary components: an active power controller and a generator system. The generator system plays a critical role in emulating the response of the wind turbine from the grid side, enabling the necessary adjustments to be made in real time. Synchronously, the active power controller assumes the responsibility of adjusting the reference power (P_{ref_WT}) for each wind turbine, considering inputs such as the power plant reference power and the grid-measured power. At the core of the power plant lies the regulator for active power, which is tasked with determining the reference power P_{ref_WT} for each wind turbine. This critical task is accomplished by processing two vital input signals. The first input signal, ΔPc, is derived from the primary wind response and indicates the difference between the actual and scheduled power. The second input signal, derived from the AGC system, includes the mandatory secondary response (ΔPc) and the wind power available from the power balancing model. The active power controller also incorporates information on the grid measure power, as P_{meas_PCC}, in determining the reference power P_{ref_WPP} [12].

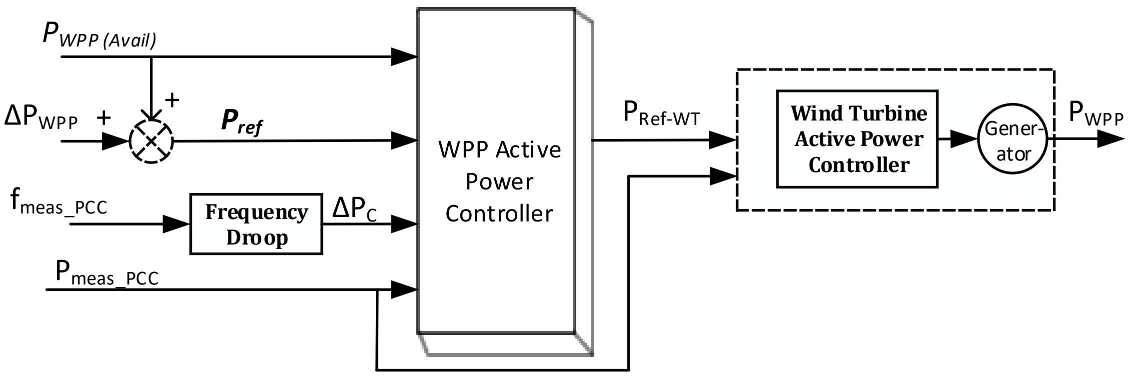

Figure 2. Wind power plant system.

The choice of wind turbines is a dominant factor in enabling AGC services, given their distinctive characteristics that facilitate their participation in such services [9]. The ubiquitous three-blade wind turbines, the most commonly used type of wind turbine, can be classified into four distinct types based on their respective energy conversion systems [8]. The first type is characterized by fixed-speed wind turbines equipped with squirrel-cage induction generators. The second type comprises fixed-speed wind turbines with wound-rotor induction generators. The third type features variable-speed wind turbines with doubly fed induction generators, while the fourth type consists of variable-speed wind turbines with full-power converters. Classifying wind turbines into these four types provides valuable insights into the options available for implementing AGC services within a wind farm. It highlights the importance of carefully selecting the type of wind turbine to ensure optimal performance and efficiency. Fixed-speed wind turbines with squirrel-cage induction generators are characterized by their straightforward and sturdy construction, which makes them cost-effective and reliable. However, they cannot manage and regulate their output power due to their dependence on a fixed rotational speed determined by the grid frequency. Therefore, they cannot adjust their power output to meet the AGC service requirements [12].

Type I turbines are similar to type II turbines in their simple design but differ in their ability to control their output power. This type of wind turbine can regulate its power output by adjusting the rotor circuit's resistance or capacitance, making it more flexible and efficient in power production. This feature allows the wind turbine to operate at a specific optimal point for maximum power capture and reduce stress on the turbine's mechanical components [9]. Type III turbines are designed to adjust their output power through a specialized control mechanism that manipulates the rotor-side converter. This converter provides active and reactive power control, allowing enhanced flexibility in managing the wind turbine's output. By implementing a converter that governs the power flow in the rotor circuit, the generator's rotor is linked to a sophisticated system that can precisely adjust the electrical frequency and voltage. This intricate manipulation of the power flow allows the turbine to achieve heightened energy efficiency and accuracy [3] compared to fixed speed. Turbines and DFIGs can operate over a wider range of wind speeds and can generate more power during low wind speeds. Wind turbines with full-power converters of the variable-speed type are equipped with the most advanced control capabilities, allowing for precise and swift adjustments to their output power. The type IV wind turbine utilizes a full-scale converter segregating the machine side from the grid. This segregation enables the optimization of rotor speed and independent control flow of active and reactive power to the grid through the grid-side converter. The full-scale converter influences the dynamic behavior of the wind turbine on the grid side. To facilitate modelling, the wind turbine generator is commonly represented as a (static) generator that can function as both a current source and a voltage source model. The static generator does not rotate, and its dynamic response is primarily shaped by the active current component and the phase-locked loop (PLL) [20].

2.2. Past Practices on the Integration of Wind Power in AGC

Numerous research works have studied control strategies for wind farms to aid in load frequency control (LFC) [3,14,21,22]. One commonly used control method is the proportional integral (PI) controller-based AGC structure, known for its simplicity and ease of application. In evaluating the performance of controllers for AGC, researchers typically investigate various control indices such as overshoots, settling time, steady-state error, and other relevant parameters. Despite the extensive research in this area, there remains a need to investigate and develop new and innovative control strategies that can improve the performance of wind farms in the AGC. By exploring new approaches, a more efficient way can be found to optimize wind farms' contribution to secondary frequency control and enhance their integration capacity into modern power systems. Therefore, future research should explore new and innovative control strategies that can maximize the performance of wind farms in the AGC, ultimately contributing to a more efficient and reliable power system.

2.2.1. Intelligent Control Techniques

Intelligent control techniques such as fuzzy logic and neural network are proposed to address the challenges of integrating wind power into automatic generation control (AGC) systems. FLC is a rule-based approach that uses linguistic variables and fuzzy logic to capture the uncertainties and nonlinearities of the wind power generation process [5]. The fuzzy rules are derived from the expert knowledge of system operators and are used to adjust the AGC parameters in response to changes in wind power output. NNC, on the other hand, is a data-driven approach that uses artificial neural networks to learn the nonlinear relationships between the wind power output and the AGC parameters. The neural network is trained using historical data and can predict the AGC parameters required to maintain grid stability based on the current wind power output [23–26]. The scholarly article [23] produced a distinctive PI regulator employing fuzzy logic to optimize AGC in a two-area power grid utilizing wind farms equipped with DFIGs. The research established that the fuzzy approach exhibited superior performance in regulating frequency during different load variations and wind levels compared to a basic PI controller. However, the expert knowledge base construction process may limit the efficacy of the fuzzy logic approach. To surpass the aforementioned constraint, reference [24] proposed a combined control technique that utilizes the Jaya algorithm to integrate a fuzzy logic controller with a PID regulator. This new methodology was then implemented in an AGC power grid system comprising three distinct areas featuring wind farms. The proposed regulator was trained for a broad spectrum of operating conditions and load changes, which aided in optimizing its performance. These intelligent methods have exhibited their efficacy in improving the AGC of wind-integrated power systems, and they are likely to continue being a vigorously explored area in the future.

Likewise, in Reference [25], a sophisticated non-linear recurrent ANN is exemplified by utilizing off-line data to augment the contribution of wind farms in the AGC of a multi-area grid. The suggested controller evinces enhanced frequency performance, as measured by notably reduced undershoot and settling time and expedited oscillation damping when juxtaposed with the traditional PI regulator. Similarly, a different supervised-learning-based controller is recommended in Reference [26] for AGC in a multi-area grid with wind power integration. Specifically, the least square support vector method is proposed as a novel solution. This newly proposed controller demonstrates remarkable efficiency in regulating frequency compared to the AGC based on a multi-layer perceptron neural network. The proposed method capitalizes on the power of support vector machines to deliver an impressive performance, thereby serving as a promising solution for effective AGC in multi-area power systems that incorporate wind power.

2.2.2. Soft Computer Control Techniques

To enhance the already commendable performance of AGC systems, the utilization of parameter-optimizing techniques has become ubiquitous. These techniques fine-tune the control parameters of power system models, thus optimizing their performance and ensuring that they operate at peak efficiency. By identifying the optimal values for the model parameters, AGC systems can achieve unparalleled levels of precision and reliability in regulating the output of power-generating units and maintaining the delicate balance between generation and demand. In a groundbreaking study, researchers cited in Reference [27] employed a simple yet effective parameter optimization method that relied on the integral of the square error index to coordinate the integration of wind turbines with the AGC system of an isolated power system. The success of this method was demonstrated through its ability to handle high levels of wind farm penetration and effectively integrate DFIGs into the AGC mechanism. Conversely, in Reference [28], a more complex dynamic participation method was proposed that harnesses the power of DFIG-based wind farms to optimize AGC performance. This cutting-edge approach boosts the stability margin of the system and provides appropriate damping for seamless frequency response. While these studies prove the immense contribution of DFIGs in the grid's AGC, the former study's limitation is its simple optimization process. Nonetheless, the pioneering nature of these studies highlights the ongoing efforts to leverage modern technologies and advanced techniques in the quest to revolutionize power systems' control mechanisms.

Various advanced metaheuristic optimization techniques are employed to address the limitations of the simple optimization methods used in some wind turbine systems for contributing to AGC. These techniques leverage the power of advanced algorithms to optimize the performance of wind turbines in AGC systems, ensuring that they operate at maximum efficiency and effectiveness. Among the techniques utilized are ACO [29], CRSPO [30], IPSO [31], OGSA [32], and GA [33]. Each of these techniques offers unique advantages, depending on the specific requirements of the wind turbine system and the AGC application. Applying these advanced optimization techniques has significantly enhanced the performance of wind turbines in AGC operations, enabling them to contribute to the maintenance of system frequency and balance. By leveraging the power of advanced algorithms and computational methods, the full potential of wind turbine systems in AGC operations can be realized, paving the way for even more effective and efficient power generation in the future. Reference [29] presented a novel approach known as ALO to optimize the grid parameters of the trajectory following the regulator in the design of wind turbines. This method was significantly more effective than PI and PID regulators in reducing peak overshoot and settling time for frequency performance.

2.2.3. Model Predicative Control Methods

Implementing the model predictive control (MPC) approach has proven effective for integrating wind farms into AGC systems. This is evidenced by research conducted in the field, as indicated in references [34–36]. The MPC optimization process is executed at each time step, calculating a fresh control input vector for the system, considering system constraints. MPC is extended to AGC applications in both single- [34] and multi-area power systems [35]. It successfully optimizes the performance of systems incorporating DFIG-based wind farms. Additionally, the approach considers variations in the parameters of the governor and turbine, as well as fluctuations in load demand. The utilization of MPC for AGC in a grid with wind power demonstrates a high degree of superiority in control system design. Through this approach, the control system can respond to changing conditions in real time, ensuring that the system operates within safe and efficient parameters. Moreover, MPC can potentially enhance the power system's operational efficiency and reliability, contributing to a more sustainable and secure energy infrastructure. To augment the efficacy of the MPC methodology when applied to AGC systems that incorporate wind farms, a distributed MPC technique known as DMPC is implemented, as described in the literature [36]. The DMPC approach partitions the system into several subsystems, each governed by a local MPC controller. This decentralized approach offers several advantages over the conventional central or simple MPC strategies, such as more resilience to perturbations and more proficient utilization of system resources, which translates into superior performance of the AGC. The distributed nature of the DMPC allows for real-time, precise control over each subsystem, which enriches the inclusive stability and reliability of the system as a whole. Thus, DMPC represents an innovative and potent solution for improving the performance of MPC-based AGC systems, including wind farms.

2.2.4. Control Approach Integrating BESS and FACTs Devices with Wind Energy

Energy storage systems have recently gained significant attention and appreciation due to their ability to accumulate and discharge energy according to demand. These systems are considered one of the most advantageous and efficacious solutions to mitigate the adverse effects of wind power variability and ensure optimal power grid operation. With energy storage systems, power grid operators can offset the irregularities and fluctuations of wind power and enhance their control over the frequency and AGC performance, thus improving the overall grid stability and reliability. Reference [37] provides evidence of successfully incorporating a 34 MW BES into a 51 MW WF in Japan. Integrating a large-scale ESS enhances the system's efficiency by absorbing and releasing energy as required, ensuring stable and reliable operation. As the global demand for renewable energy continues to rise and more wind farms are installed, using energy storage systems as supplementary energy sources are becoming increasingly popular. These systems are crucial in attaining optimal frequency control and influencing AGC in power grids.

Although numerous energy storage technologies exist, research suggests that RFB, flywheels, CES, and SMES are the most effective at contributing to AGC in wind farms. In addition to ESS, there is significant potential for frequency control enhancement in multi-area power grids using FACTS devices. Considering the need for managing power flow across tie-lines, FACTS devices can substantially enhance frequency control in power systems. Similarly, ESSs and FACTS devices are currently considered the most powerful instruments for wind farms to contribute to the AGC service of power systems. Supporting this assertion, the findings in Reference [38] have successfully integrated flywheel storage systems with wind farms based an AGC network. This has led to a shortened settling time and more efficacious damping of frequency deviations, accentuating the potential advantages of this technology for frequency control in wind farms. Reference [39] showcases the coordinated design of RFB and AGC to minimize frequency deviation in multi-area power grids incorporating wind farms. The study demonstrates the substantial improvement in frequency response and control of wind-integrated power grids through joint optimization of RFB and AGC. The coordinated design uses advanced optimization techniques to reduce frequency deviation grids, ensuring steady and dependable operation. Additionally, the research accentuates the potential of ESSs such as RFB, when combined with AGC, to effectively alleviate the impact of wind power uncertainties on power grid stability. The collaborative design of AGC and RFB has the potential to present a comprehensive solution to the challenges associated with integrating wind farms into power grids, thereby leading the way to a more dependable, efficient, and sustainable energy future.

Although earlier research has thoroughly explored the incorporation of ESSs into wind farms to tackle the problem of AGC, these studies have predominantly concentrated on single-area networks. Nonetheless, using ESSs in one region may not considerably influence the frequency behavior of other regions, and installing these systems throughout all areas may be excessively costly. Therefore, it is rational to utilize FACTS devices with AGC of wind networks to augment the regulation of tie-line power, thereby considerably facilitating the frequency performance of the entire grid. By regulating power flow across tie-lines, FACTS devices can ensure that the power system's frequency remains stable despite intermittent wind energy. This integrated approach is a cost-effective solution that can significantly enhance the efficacy of AGC in power grids with multi-areas and wind farms. Reference [40] presents significant data that validate the power of a coordinated design approach that harmoniously merges a TCPS and SMES system within a particular geographical location while facilitating dynamic participation of wind farms in a deregulated power grid with two areas. Reference [41] examined a comparable technique by integrating SMES systems into each power grid region with two areas. However, such utilization raises the total cost of the system's operation, considering ESSs are relatively costly. Nonetheless, the utilization of these integrated systems can produce considerable enhancements in the control of frequency and AGC performance in multi-area grids with wind farms, ultimately advancing the dependability and efficiency of the power grid. Moreover, a thorough examination of the current scholarly works in Section 2 is expounded in Table 1, which encompasses the kind of power generation units utilized in the power grid, the methodology employed in configuring the system, and the optimization strategies used.

Table 1. Summary of AGC schemes with wind energy.

Ref No.	Type of Power System	Areas	Energy Generation Sources	Additional Devices	Controller Approach
[29]	Traditional	2	Wind, thermal	--	ACO-based PI
[23]	Traditional	2	Wind, thermal	--	Fuzzy-based PI
[24]	Traditional	2	Thermal, wind	--	Fuzzy-based PID
[25]	Traditional	2	Thermal, wind	--	NLR-ANN
[26]	Traditional	2	Thermal, wind	--	LSVM-based PI
[27]	Traditional	1	Thermal, wind	--	Simple PI
[28]	Traditional	3	Wind, Thermal, gas, hydro	--	Simple PI
[30]	Traditional	2	Wind, thermal	--	CRSPO-based I
[31]	Traditional	3	Wind, thermal	--	IPSO-based PI
[32]	Traditional	4	Wind, thermal, gas, hydro	--	OGSA-based PID
[33]	Deregulated	2	Wind, thermal, hydro	--	GA-based PI
[34]	Traditional	1	Wind, thermal	--	MPC
[35]	Deregulated	2	Wind, thermal	--	MPC
[36]	Traditional	3	Wind, thermal	--	DMPC
[39]	Deregulated	2	Wind, thermal, and hydro	SMES, TCPS	CRPSO-based I

Abbreviations: NLR-ANN: non-linear recurrent ANN, LSVM: least squares vector machines, CRSPO: craziness-based particle swarm optimization.

3. Automatic Generation Control (AGC) and Flexible Loads

Non-conventional loads, including cold storage power plants (CPL), electric vehicles (EVs), and heat pumps (HPs), possess dynamic load characteristics, enabling their consumption patterns to be conveniently adjusted in accordance with the system's requirements [13]. Additionally, these loads exhibit adaptable consumption patterns that can be regulated externally or locally. Moreover, their energy storage capabilities enable them to store energy during low-demand periods and dispense it during peak-demand periods, providing a promising solution to the challenges faced by grid operators [20]. As per the research presented in [15], a study conducted on the modern Danish power system has demonstrated that flexible consumption units, such as cold storage and electric vehicles, have the potential to offer ancillary services, mainly regulation services, which include secondary and tertiary services.

These services aid in mitigating the challenge of forecasting and overseeing large-scale integrated systems with wind energy. This, in turn, reduces the overall expenses of the system by curbing the generation from power plants with conventional generating units. The study has deduced that consumption units can alter energy distribution for multiple hours to provide grid-supporting services while preserving their core function. In Denmark, flexible load units, as of 2020, comprised 200 MW of CLUs and 75,000 EVs, equivalent to 600 MW. This highlights the ability of flexible loads to respond to peak-hour demands and strategically redistribute the load to optimize power flow in grids, thereby reducing the need for reserves and enhancing the reliable operation of the system without incurring additional expenses [15,16]. This study introduces a theoretical model, as depicted in Figure 3, which promotes the integration of adaptive load systems into the power grid. This system incorporates two inputs: one from a measurement file and the other from the AGC unit. Integrating adaptable load systems into the power grid ensures efficient energy distribution and helps reduce reliance on reserves, thus enabling stable system operations without incurring extra costs. Depending on the signal received from the AGC unit, the flexible load units can adjust the load value to achieve the desired system response by increasing or decreasing it.

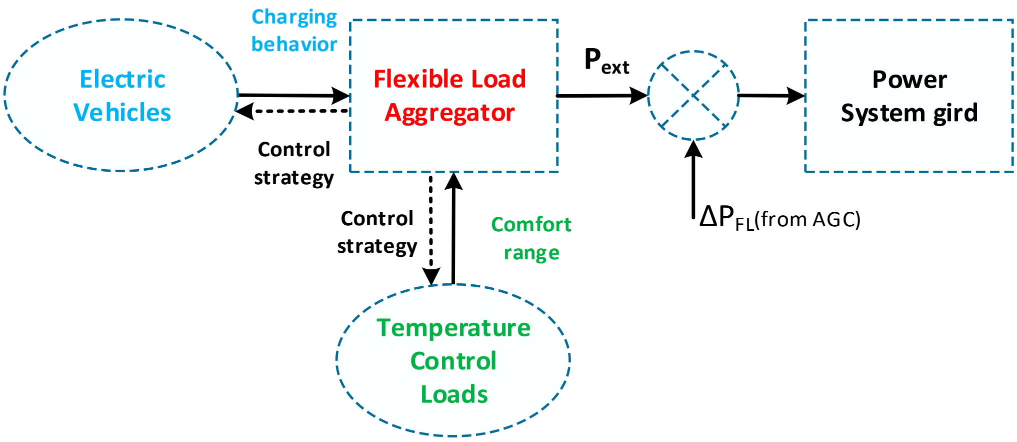

Figure 3. Power system with flexible load.

3.1. Electric Vehicles as Flexible Loads

Due to their controllable and flexible charging patterns, electric vehicles (EVs) can significantly provide ancillary services, including AGC. EVs can participate in AGC services by responding to the control signals from the grid operator to adjust their charging and discharging rates. This can provide various benefits to the grid, including load balancing, peak shaving, and frequency regulation. Multiple investigations have explored the possibility of EVs contributing to AGC services. For instance, a study by [20] established the viability of leveraging EVs to offer frequency regulation services by modifying their charging and discharging speeds based on the frequency signals obtained from the power grid. Correspondingly, a study by [42] proposed a hierarchical control structure to synchronize EV charging and discharging to provide AGC services. This study demonstrated that EVs could help minimize the ramp rate of conventional power plants and advance the overall steadiness of the power system. These studies underline the potential benefits of incorporating EVs into the power grid as an AGC resource. The ability of EVs to function as flexible loads and swiftly adjust their charging and discharging rates makes them promising candidates for providing AGC services. The power system can operate with enhanced stability by utilizing EVs in AGC services and minimizing the need for additional reserves. The work described in [43] focuses on managing EV charging for user satisfaction and smart grid stability. It explores using bidirectional power flow between EVs and the grid (G2V and V2G) to utilize unused electric power. A peak load management model (PLM) is proposed for scheduling EV charging and discharging based on power demand, timing, and location. Extensive MATLAB simulations validate the effectiveness of the proposed approach, considering factors such as vehicle mobility, time-of-use pricing (TOUP), and urban scenarios.

Furthermore, integrating EVs into the AGC services can reduce expenses by decreasing the need for traditional thermal power plants. Therefore, using EVs for AGC services can aid in developing a more efficient, sustainable, and cost-effective power grid. In [44], the authors presented a theoretical structure for integrating EVs into extensive power system grids encompassing the technical facets of grid operation and the electricity market environment. The authors also presented an in-depth discussion regarding the potential advantages and difficulties of the integration, explicitly focusing on minimizing the anticipated errors. Their work highlights the importance of addressing the potential technical and market-related barriers to ensure the successful integration of EVs into the power system. Ultimately, the authors' theoretical framework lays the groundwork for future research on integrating EVs into the power grid, advancing sustainable, efficient, and cost-effective power systems.

Figure 4 shows the integration of multiple electric vehicles (EVs) in an electrical vehicle area (EVA). EVA denotes a specific geographic region or location where a substantial number of electric vehicles (EVs) are clustered and managed by a central control center.

The EVs are linked to a central system that is accountable for managing and enhancing their charging and discharging functions within an EVA. This system receives instructions from an AGC system, which is accountable for harmonizing the power supply and demand in the electrical network. Upon receipt of the instructions, the EVA control center leverages a built-in algorithm to allocate the instructions to each EV, considering various factors, such as the vehicle's battery capacity, charging level, and distance to the target location. This process ensures that every EV is prepared for usage when required without overburdening the electrical grid [45]. Therefore, for the electrical vehicle area (EVA) to efficiently execute its functions during the dispatch period, it is crucial to have comprehensive information on each electric vehicle (EV) under its jurisdiction.

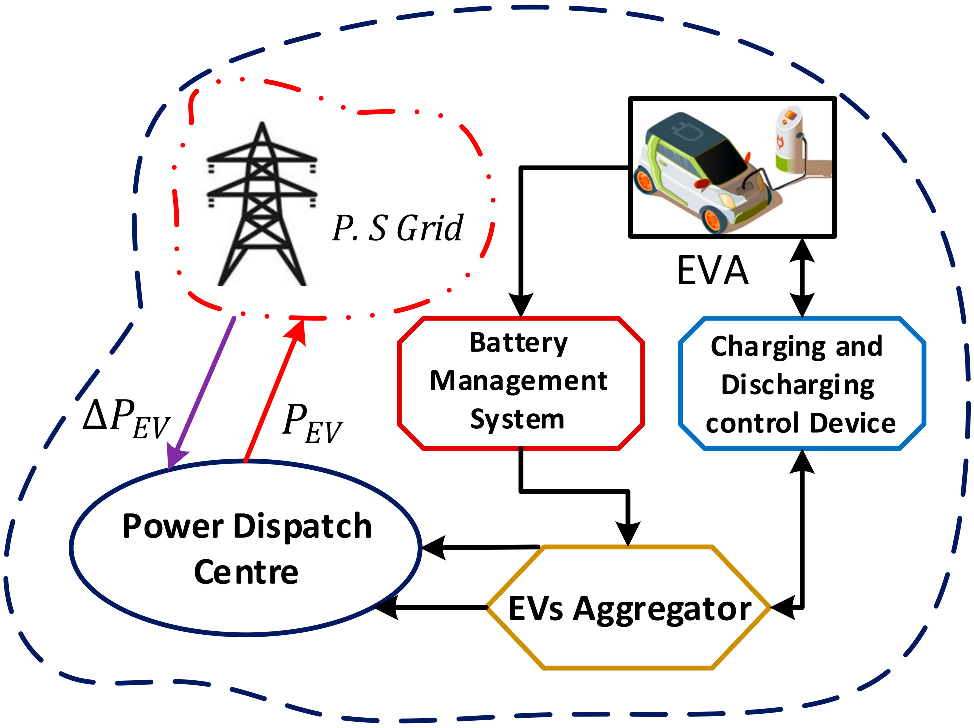

Figure 4. EVA model.

In this particular study, for the better understanding of the reader, the EVA's AGC system model is epitomized by a first-order transfer function, which takes into account two crucial parameters: the frequency gain characteristics parameter (K_{EV}) and the charging and discharging time constant (T_{EV}) [20]. The customary reaction time for the EVA prototype is typically within the 7 to 8 s spectrum, which can be attributed to two principal determinants. Firstly, the process involved in the aggregator dispatching received orders to individual EVs is time consuming. Secondly, the communication channels tend to induce a time delay, typically in the order of milliseconds. It is, therefore, vital to ensure that the EVA has accurate and up-to-date information on each EV to optimize the performance of the AGC system. By factoring in various time delay elements and integrating them into the EVA model, it is possible to improve the efficiency and dependability of EV management and control within the electrical grid.

The electrical vehicle area (EVA) is configured to offer operating reserves of positive and negative value in response to deviations in the system frequency. Positive regulation reserves (PRR) are utilized when there is a shortfall in generation within the system, while negative regulation reserves (NRR) are employed when generation is required to be reduced [20]. Figure 5 illustrates the calculation of PRR and NRR, which is performed by taking the variance between the present charging power ($P^i_{EV,t} < 0$, charg. mode) or discharging power ($P^i_{EV,t} > 0$, discharge. mode) to the maximum discharging power

($P^i_{\Delta t} > 0$) and charging power ($P^i_{\Delta t} < 0$) for a planned interval Δt. To execute PRR operation, the EVA system curtails the loads linked to EVs or employs V2G technology to export stored charge from EV batteries back to the grid. This strategy can mitigate the issue of insufficient power generation in the system.

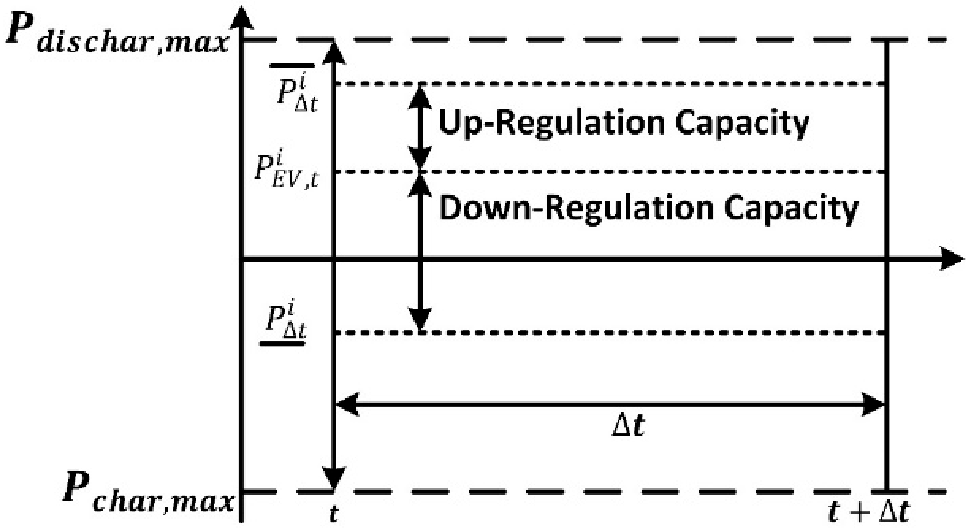

Figure 5. Reserves calculation (positive and negative).

In contrast, for executing NRR operations, the EVA amplifies the loading impact of EVs to enable the transmission of power from the grid to the batteries. This method can alleviate the surplus power generation in the system. The aggregator assumes a pivotal role in achieving PRR and NRR by accumulating the impact of all EVs during a specific time frame. This function is of paramount importance in the EVA system. The aggregator utilizes algorithms to ensure that the PRR and NRR operations are executed with maximum efficiency and efficacy while considering multiple constraints, such as the current state of charge of the EV batteries and the user's requirements. To achieve the PRR operation, two important limitations are considered, including what the current battery state of the charge (SoC^i_t) is according to the needs of the user ($SoC_{i,n}$). This means that for a time ($t + \Delta t$):

$$SoC^i_t \geq SoC_{i,n} \tag{1}$$

The second constraint involves the degradation of the battery, which is often caused by the charging cycle. To tackle this issue, the depth of discharge is carefully managed to balance the required regulatory capacity and the preservation of battery health. In practical terms, the depth of discharge power is commonly set at 60% to achieve this equilibrium.

$$SoC^i_{mi,t+\Delta t} \geq 40\% \tag{2}$$

The formula below is applied to determine an individual EV's positive regulation reserves (PRR) for a specific time (Δt).

$$P^i_{PRR} = P^i_{\Delta t} - P^i_{EV,t} \tag{3}$$

$$\text{Here, } P^i_{\Delta t} = \left\{ \begin{array}{c} min(P_{c,max}, \frac{(\Delta SoC^i_t \times C_i)}{\Delta t \times eff})\ \Delta SoC^i_t > 0 \\ max(P_{dic,max}, \frac{(\Delta SoC^i_t \times C_i)}{\Delta t \times eff})\ \Delta SoC^i_t < 0 \end{array} \right\} \tag{4}$$

The notation ΔSoC_t^i implies that it is possible to increase the maximum capacity of electric vehicles (EVs) for a given time interval Δt.

$$\Delta SoC_t^i = 100 - P_{EV,t}^i \tag{5}$$

Taking this into consideration, the overall PRR of electrical vehicle areas (EVAs) can be computed as follows:

$$\Delta P^i_{PRR(total)} = \sum_{i=1}^{N} P^i_{PRR} \tag{6}$$

Likewise, the calculation of NRR for an individual EV during the time interval of Δt is determined as follows:

$$P^i_{NRR} = (P^i_{EV,t} - P^i_{\Delta t}) \tag{7}$$

$$\text{Here, } P^i_{\Delta t} = min(P_{charg,max}, \frac{(\Delta SoC_t^i \times C_i)}{\Delta t \times eff}) \tag{8}$$

Taking this into consideration, the overall NRR of electrical vehicle areas (EVAs) can be computed as follows:

$$\Delta P^i_{NRR(total)} = \sum_{i=1}^{N} P^i_{NRR} \tag{9}$$

It is worth mentioning that the constraints for NRRs are primarily associated with the maximum charging power of the charger and the *SoC*.

$$SoC^i_{min,t+\Delta t} \leq 100\% \tag{10}$$

3.1.1. Past Practices on EVs Integration in AGC

Numerous research works have explored the application of electric vehicles (EVs) in frequency regulation services. These investigations are classified into distinct groups based on several factors, including but not limited to the system architecture, bidirectional vehicle-to-grid (V2G) technology, revenue maximization, optimization algorithm, minimal battery degradation, schedule, and principal objective. Such factors are essential in defining and understanding the nature and scope of the research, as they provide the necessary framework for investigating the latent potential of EVs in frequency regulation services.

Centralized and Distributed Control Techniques

The academic literature proposes various dispatching strategies for the efficient use of EVs for secondary frequency regulation. These strategies can be characterized as centralized and distributed modes [46]. In the centralized mode, a single aggregator supervises a group of EVs parked at the charging station. On the other hand, the distributed mode involves EVs stationed in communal areas, and the system operator monitors and manages them. The hierarchical approach involves transitional accumulation layers that enable effective coordination of control signals concerning the aggregators and EVs. This approach enhances the system's suppleness and scalability, allowing it to handle more EVs and adapt to changes in demand and supply more efficiently. In [47], a compelling representation of a hierarchical control system designed to manage electric vehicles (EVs) for AGC services is provided. The physical layer of this system includes a substation unit, aggregators, and charging stations, which operate collectively to calculate regulation signals. Once these signals are determined, the control layer bifurcates them and assigns them to the corresponding physical entities. Mixed-integer linear programming (MILP) is implemented to optimize EV charging and discharging patterns. This optimization method employs a mathematical model that factors in various constraints and objectives to achieve an optimal outcome that maximizes the system's efficiency. The utilization of MILP in this context ensures that the EVs' charging and discharging are synchronized in a manner that mitigates expenses, reduces energy loss, and preserves the stability of the power grid. Additionally, a control mechanism based on the distributed technology of the concept of V2G is introduced [48]. The proposed system aimed to utilize EV batteries as a decentralized energy storage solution, thus facilitating RES integration and ensuring the system's reliability. An energy supervision model was employed to accomplish this, which integrated a day-ahead EV charging and discharging schedule to improve the controlling capabilities. This model considers several factors, such as the charging routines, the projected travel distances of the EVs, and the availability of RESs. Yao [49] provided an exposition in their publication [47], elucidating how EVs can aid the United States' ISO in regulating grid frequency. This is attained by modifying the charging and discharging patterns of the EVs in response to a centralized AGC signal in real time. This method utilizes EVs' flexible and adaptable nature and provides a pragmatic approach to stabilizing the power grid's frequency. In [50], an innovative energy management protocol (EMP) that integrates renewable energy sources and electric vehicles (EVs) into the power grid is presented. The EMP efficiently manages EV charging and discharging from a wind-powered energy storage system using advanced machine learning (ML) and game-theoretic (GT) algorithms. ML-based wind power forecasting and GT-based power dispatching optimization ensure reliable and efficient grid operation. Empirical evidence from case studies supports the effectiveness of the proposed approach for accurate and efficient power management.

Additionally, a recent study proposed a novel controller [51] that clusters EVs based on their state-of-charge (SoC) and daily travel average. This assembling method aims to identify EVs with similar characteristics and coordinate their participation in frequency regulation activities. This methodology offers a pragmatic resolution for effectively handling a substantial fleet of electric vehicles while concurrently guaranteeing the steadfastness of the electrical power system. In this instance, a multi-faceted optimization model predicated on the particle swarm algorithm is employed to curtail the discrepancies in the grid's frequency while simultaneously catering to the power requirements of EVs. Furthermore, Neofytou et al. scrutinized the practicality of using electric vehicles (EVs) for disseminated frequency maintenance in a remote power grid located on Cyprus Island [52]. This research revealed the advantages of leveraging the combined power output from EV batteries to bolster the grid's performance through the vehicle-to-grid (V2G) mode of operation while accounting for user preferences.

Control Techniques Focusing on PayBack Schemes

In the modern scholarly literature, several economically minded strategies are suggested to motivate automobile owners to engage in frequency regulation services in addition to the previously mentioned dispatching methods that regulate frequency. In [53], Han and colleagues analyzed the practicality of employing V2G operations for regulating grid frequency, focusing mainly on the monetary advantages for EV owners. The research underscored the possibility for the system operator and EV owners to earn revenue by incorporating EVs into ancillary services.

By utilizing V2G operations, EVs can function as a dependable energy source to bolster the grid's stability, offering car owners an economic advantage through active involvement. A state-of-the-art MPC system has been introduced for EV aggregators, with a comprehensive overview of its workings in [54]. This system is designed to optimize the capacity payment for EV aggregators while also considering the prevailing regulation capacity prices. The MPC system employs an advanced prediction model, which is significantly improved compared to simpler predictive models used in the past. By leveraging this improved prediction model, the capacity payment for EV aggregators is boosted by an impressive 4.3% compared to the previous system that relied on less advanced prediction models. Further, an extensive and all-encompassing investigation into the techniques for utilizing EVs in the SFR is undertaken and outlined in great detail in [55]. This investigation has comprehensively analyzed the subject matter by categorizing the various techniques into two primary aspects: frequency-oriented and economic-oriented. The frequency-oriented aspect aims to maintain the electrical system's frequency at its designated nominal value, typically 50 Hz or 60 Hz. This approach ensures the stability and consistency of the frequency, enabling reliable operation and optimal system performance. On the other hand, the economic-oriented aspect highlights the financial advantages of integrating EVs in frequency regulation. This approach emphasizes the potential economic benefits of involving EVs in ancillary services, ultimately optimizing the system's economic efficiency.

Soft Computing Control Techniques

EVs' participation in the service of frequency regulation has emerged as a prominent area of interest among researchers across the globe. Therefore, a wide range of optimization models has been formulated and implemented to investigate the various objectives that can be attained through this technological advancement. These models comprise complex mathematical frameworks such as mixed-integer linear programming (MILP) models [47,56,57], non-linear programming (NLP) models [48], and stochastic MILP models [58]. MILP models are extensively employed to optimize the EV's performance in the regulation of frequency, with researchers utilizing this technique to develop diverse strategies to achieve multiple objectives.

These objectives encompass enhancing the economic benefits of EVs' participation in frequency regulation, maintaining a balance between the energy demand and supply in the electrical grid, and improving the overall system stability. Moreover, NLP models have also been utilized to address the intricacies of optimizing the performance of EVs in frequency regulation, considering the dynamic and non-linear characteristics of the electrical grid. This approach aims to identify the optimal operating conditions of the EVs involved in frequency regulation while considering the physical constraints and limitations of the system. Additionally, researchers have explored the potential of stochastic MILP models, which are designed to account for the stochastic nature of the electrical grid and the uncertainty associated with EVs' participation in the regulation of frequency. This approach offers a more realistic representation of the actual dynamics of the electrical grid, enabling the optimization of EVs' performance under varying and unpredictable conditions.

An example of the efficiency of employing a fleet of EVs for frequency support is evidenced in a study utilizing a Mo-PP [59]. By using an interior point method to address the decomposed sub-problems, the researchers demonstrated the potential of EVs to regulate system frequency services and optimize the performance of the electrical grid. A recent study proposed a state-space model utilizing the Markov transition matrix to estimate EVs' regulation capacities and state transitions [60]. This model enables accurate real-time control of aggregated EVs with minimal computational loads. However, it is essential to note that this approach may not prioritize real-time communications, which could lead to less pressure on the system to respond quickly to changing conditions. In recent years, many state-space models have been proposed for accurately estimating the frequency regulation capacity of electric vehicles (EVs) participating in frequency regulation services. One such model, introduced in [42], is an improved version that accounts for both the preferences of EV owners and the potential errors in the modelling process. By incorporating EV owners' preferences, this model considers that EVs may have different charging patterns and may not always be available to participate in frequency regulation services. The model also addresses potential errors in the modelling process that may arise due to limitations in the data or computational resources. Further, this model also considers the progressive state recovery in frequency regulation. In other words, it is based on the belief that the electrical grid may take some time to recover from disturbances and return to its nominal operating state. This is an essential consideration in designing control strategies for frequency regulation services, as it can help ensure that the system remains stable and reliable even under adverse conditions. To provide a summary of the various strategies mentioned above, Table 2 presents a comprehensive comparison of these dispatching methods, taking into account several key factors such as system architecture, bidirectional vehicle-to-grid (V2G) capabilities, maximum revenue potential, optimization algorithm employed, minimum battery degradation, scheduled time frames, and primary objectives.

Table 2. EVA-based AGC control strategies for frequency regulation.

Ref No.	System Architecture	Max Revenue	Degradation of Battery	Time Schedule	Controller Approach	Main Objective
[47]	Hierarchical	Yes	Yes	Real-time	MILP	Economic
[48]	Distributed	Yes	No	Day ahead	NLP	Economic
[49]	Centralized	Yes	Yes	Real-time	MILP	Frequency
[54]	Centralized	Yes	No	Real-time	MILP	Frequency
[56]	Distributed	Yes	Yes	Day ahead/real-time	NLP	Economic
[58]	Centralized	Yes	No	Day ahead	Stochastic MILP	Frequency
[59]	Centralized	No	Yes	Real-time	Interior point method	Frequency
[61]	Centralized	Yes	No	Real-time	Gurobi	Frequency

MILP: mixed-integer linear programming, NLP: non-linear programming.

3.2. Thermostatically Controlled Loads (TCLs) as Flexible Loads

The proliferation of renewable power generation has brought to light a pressing issue: the need for secondary regulation services to maintain grid stability. This has led to a growing consensus that demand-side resources, such as residential thermostatically controlled loads (TCLs), must provide zero-emission regulation services integral to successfully integrating renewable energy sources. TCLs, which include a range of appliances such as air conditioners (ACs), heat pumps, water heaters, and refrigerators, are responsible for approximately 20% of the United States' overall electricity consumption [62], highlighting their significant potential to deliver a range of ancillary services. TCLs are uniquely positioned to provide flexibility to the grid, as they are relatively easy to control and can be adjusted in real time. As renewable energy sources become increasingly prevalent, the need for demand-side resources, such as TCLs, to provide regulation services will only grow. Hence, using TCLs for ancillary services helps maintain grid stability and promotes the shift towards zero-emission energy systems, making them a critical component of the transition to a cleaner energy future.

Secondary reserves can be tapped from thermostatically controlled loads (TCLs) through a demand response process. Demand response allows grid operators to remotely adjust TCL temperature settings during periods of high electricity demand or low supply. By temporarily reducing energy consumption from TCLs, grid operators can free up capacity that can be used as secondary reserves to maintain grid stability. This process is typically done through automated controls (AGC) communicating with TCLs via a communication network. In addition to reducing peak demand and providing secondary reserves, demand response programs such as lower electricity rates or rebates can incentivize the participation of consumers. Cold storage units have the potential to furnish the necessary ancillary services due to their temperature-controlled properties. These loads may be regarded as adaptable loads that possess a degree of regulatory capability. As renewable energy sources (RESs) are introduced on a large scale, the services delivered by cold storage units reduce dependence on conventional energy sources and enhance the system's flexibility, promoting a secure power management framework. The energy balance for cold storage can be characterized as follows [63].

$$Yt_p \frac{dTt_p}{dt} = \frac{dQ_l}{dt} - \frac{dQ_e}{dt} \quad (11)$$

In conformity with Equation (11), Y is employed to indicate the entire weight of frozen commodities, whereas the distinct warmth capacity of the frozen goods is symbolized by tP. Furthermore, Q_l and Q_e pertain to the chilling potential applied to the atmosphere and the refrigerated room, in that order. In addition, Equations (12) and (13) establish the feasible burdens that cold storage systems can receive, while Equations (14)–(16) demonstrate the state and authority factors [63].

$$\frac{dQ_l}{dt} = (UA)_{am-c.}(T_{am} - T_a) \tag{12}$$

$$\frac{dQ_e}{dt} = (UA)_{cr-e.}(T_{cr} - T_e) \tag{13}$$

$$T_{cr,min} \leq T_{cr} \leq T_{cr,max} \tag{14}$$

$$0 \leq T_{cr} - T_e \leq \infty \tag{15}$$

$$0 \leq \frac{dQ_e}{dt} \leq (UA)_{cr-e.} max(T_{cr} - T_e) \tag{16}$$

Equations (13) and (16) elucidate the coefficient for thermal conduction as UA, and T_{am} denotes the temperature of the encompassing atmosphere, T_{cr} represents the temperature range for the cold storage area ($T_{cr,min}$, $T_{cr,max}$), and T_e indicates the refrigerant temperature at the boiling stage. The temperature at the evaporative stage is managed by the system operator of the compressor, ensuring that $T_{cr} \geq T_e$. The equation at the balance of energy considers the dynamics associated with and constraints related to cold storage. The compressor's energy depletion prevails in the system, determined by the mass flow rate of the refrigerant and its corresponding change in energy content. Equation (17) represents the refrigerant's mass flow rate, signifying the ratio between the cooling capacity and the enthalpy change of the evaporator [63].

$$m_r = \frac{\frac{dQ_e}{dt}}{h_{oe}(T_e) - h_{ie}(T_c)} \tag{17}$$

The refrigerant's mass flow rate is signified as m_r in Equation (17), while Equation (18) furnishes a phrase for the alteration in energy content (W_c), which may be computed from the contrast in the refrigerant's enthalpy at the compressor inlet, h_{ic}, and exit, h_{oe}. It is of note that the isentropic efficiency, n_{ic}, is conjectured to remain constant within the designated operational spectrum.

$$\frac{dW_c}{dt} = \frac{m_{ref}(h_{oe}(T_e, P_c) - h_{ic}(T_e)}{n_{ie}\left(\frac{P_c}{P_e}\right)} \tag{18}$$

Within Equation (8), P_c and P_e represent the pressures of the refrigerant at the input and output of the compressor, respectively.

Past Practices on Integrating TCLs in AGC

The research on the collective behavior of a sizable population of thermostatically controlled loads (TCLs) can be traced back to the 1980s, when researchers began to investigate the aggregated response of these loads to varying power system conditions. Reference [64] presents an innovative modelling methodology rooted in physical principles. This approach was introduced to investigate the phenomena of cold load pickup and payback, which are commonly observed in thermostatically controlled loads (TCLs) following a power outage. The researchers employed a sophisticated system of interconnected Fokker–Planck equations designed to simulate the probability density of temperature dynamics in a sizable population of TCLs. By utilizing this powerful tool, the researchers gained insight into the complex and nonlinear behavior of TCLs, allowing them to develop a more comprehensive understanding of the mechanisms driving cold load pickup and payback [65]. This study employed a statistical methodology to construct a dynamic model for aggregated space heating systems or air conditioners based on two key rationales. Firstly, these systems substantially impact power system dynamics after a power outage. Secondly, owing to their inherent energy storage capabilities, they are frequently utilized for load shedding as part of a comprehensive load management scheme. The utilization of aggregated TCLs for ancillary frequency services has been the focus of considerable research interest over the last few decades [66–68]. The aggregation of demand-side loads can be managed through decentralized, centralized, and distributed methods. Decentralized control presents a simplistic means of designing a control system where thermostatically controlled loads (TCLs) respond to power requirements based solely on confined measurements [66]. However, achieving coordination among aggregators with fully decentralized control can pose significant challenges. On the other hand, centralized control is extensively proposed for demand response (DR) and offers diverse design functionalities for TCLs. Design considerations for a centralized load controller that provides continuous regulation reserves for thermostatically controlled appliances are elucidated in [66]. In contrast, a centralized load-following control strategy for heterogeneous TCLs is proposed by [67]. In [69], current demand-side management (DSM) methodologies in modern power systems are examined and categorized, and avenues for future research are proposed. The work also highlights critical aspects such as standardization, regulations, data privacy, and cybersecurity, emphasizing their relevance to DSM and its impact on the energy system.

Nevertheless, centralized control has limitations, including the computational and communication burden it entails, as well as the low fault tolerance of the central controller. In contrast, distributed control methods offer enhanced flexibility, reliability, and scalability, rendering them well-suited for aggregating many responsive loads. Distributed approaches are proposed to address various coordination, synchronization, and tracking control challenges in power engineering [68]. Distributed methods are successfully applied to achieve distributed secondary control of distributed energy resources in microgrids [70]. The secondary control strategy proposed is entirely decentralized, with each dispersed generator dependent solely on its data and that of a limited cohort of neighboring generators. This distributed framework eliminates the need for a central controller and intricate communication network, bolstering the system's reliability. Population-bin transition models, illustrated in [71], are an additional class of models widely employed to scrutinize the aggregation of TCLs. These models are designed explicitly for control-oriented purposes and are typically composed of high-order, linear ordinary differential equations (ODEs) that vary depending on the number of bins. In other words, these models classify TCLs based on their energy consumption levels and group them into several bins or categories. Each bin has its own set of differential equations to describe its behavior.

The incorporation of large-scale renewable energy sources into conventional power grids is accelerating at a breakneck pace. Nevertheless, the uncertainty and volatility of wind and solar power forecasting can potentially undermine the reliability and security of power systems [67]. Thermostatically controlled loads have emerged as a crucial element in delivering the requisite frequency regulation support and mitigating variability issues in renewable-energy-based power systems on a large scale. The author in [72] notes that the collective power consumption of thermostatically controlled loads (TCLs) can be synchronized to a high-frequency signal, such as the power output of a wind farm. In [3], there is a detailed and inclusive analysis of how the integration of TCLs, or thermostatically controlled loads, is implemented into the automatic generation control (AGC) system. The article discusses the key features and advantages of TCLs and how they are utilized to improve the resiliency of the power system's AGC network. It also covers the challenges faced during the integration process and how they were overcome. Basit proposed a real-time dynamic dispatch control strategy for AGC in [17] that employs cold storage units to achieve power balancing in large-scale wind-integrated grids. It is shown that integrating cold storage units into AGC services can ultimately improve grid flexibility, reduce peak demand and electricity costs, and enhance grid resilience.

A plethora of research is dedicated to developing models for TCLs and their aggregations, as evidenced by a substantial body of literature encompassing [65,73,74]. These models exhibit a broad spectrum of complexity and reliability, ranging from simplistic abstractions to highly sophisticated representations, and have found diverse applications in different control designs, validation endeavors, and simulations. Several studies have put forward battery models to address the issue of aggregate flexibility in a collection of TCLs [71]. However, these studies have not explicitly designated their battery models as approximations or endeavored to quantify the accuracy of such approximations. Furthermore, the battery models derived in these studies typically lack a dissipation term, leading to an underestimation of the aggregate flexibility of TCL collections. Our set-theoretic approach to characterizing aggregate flexibility and our accompanying quantification of the associated error via generalized battery models constitute a novel contribution to the existing body of research. In [74], the author devised a technique to achieve power balance in a large-scale integrated system by integrating demand-side and supply-side management strategies. The methodology entails employing energy storage management techniques on demand and supply fronts to guarantee equilibrium in the power system. By fusing demand-side management methods, for instance load curtailment and load shifting, with supply-side management techniques, such as generation curtailment and ramping, the system can adeptly handle unanticipated variations in demand or supply. This is particularly critical in systems exhibiting high levels of intermittent renewable energy sources, where electricity generation can oscillate considerably.

4. Proposed Power System AGC Model

To achieve an optimal, reliable, and robust power supply in an interconnected power grid, automatic generation control (AGC) is employed, which continually analyzes load variations and regulates generator output accordingly. Tie-line interchanges and frequency fluctuations are crucial parameters that necessitate periodic evaluation in AGC services. The combination of these variables forms the basis of the area control error (ACE) direct equation. The essential AGC control action involves the calculation of the $P_{ACE,k}$ value, which is represented as follows:

$$P_{ACE,k} = \sum_{j\epsilon\mathcal{A}_n} \beta_i \Delta f + (P_{ij}^{Ref} - P_{ij}^{Act}) \tag{19}$$

Equation (11) plays a crucial role in characterizing the parameter $P_{ACE,k}$, which represents the aggregated imbalance in the kth control area. This equation helps to understand the extent of the power supply and demand imbalance and take corrective measures to maintain the required power balance in the network. This parameter is obtained from the difference between the references (P_{ij}^{Ref}) and actual power (P_{ij}^{Act}) of the tie line and the deviation in the system frequency. The difference in the power references (P_{ij}^{Ref}) and the actual power (P_{ij}^{Act}) is also known as a tie-line error (ΔP_{tk}). The response of the system network to the frequency change is determined through the frequency bias constant (β_k), which is calculated collectively from the damping constant (D_k) of the system and governor droops (R_k) of the generating units ($\beta_k = D_k + \frac{1}{R_k}$). Here, D_k connotes the power system damping, which refers to the capacity of the system to assimilate the oscillations that arise from rapid fluctuations in power demand or supply. The parameter R_k, on the other hand, pertains to the governor droop, which refers to the generator's power output reduction for a given frequency deviation.

In the event of an inconsistency between the supply and demand of electricity, the speed governors take swift action to trigger the FCR, which is implemented to ensure that the frequency remains within a pre-determined range. Simultaneously, the AGC system activates and intelligently detects any fluctuations in the parameter of $P_{ACE,k}$; when fluctuations are detected, the AGC system triggers the FRR to adjust P_{ACE} accordingly. This ensures that the primary reserves are preserved for future usage. To achieve this objective, the AGC regulators must collaborate and work in a synchronized fashion to fine-tune the reference point (ΔP_{ref-Gk}) of all generators that participate in AGC operations. This precise adjustment of the reference point allows for appropriate control signals to be relayed to each generator, enabling them to operate in synchronization and maintain the stability of the grid. By utilizing these sophisticated control mechanisms, the system can respond rapidly to any variations in power demand, thus guaranteeing a robust and dependable electricity supply. In addition, the present study employs a PI controller in its AGC system to mitigate the error term P_{ACE}, as stipulated in Equation (20), and return the system to its stable operating state. The PI controller carries out this task by adjusting the output of the generators by calculating the error signal between the reference point and the actual output, followed by integrating this error over time.

$$\Delta P_{Sec} = K \cdot \Delta P_{ACE} + KT \int \Delta P_{ACE} dt \tag{20}$$

It is important to determine the values of the parameters K and T to stabilize the network's frequency at its nominal value and keep the exchange power within the predetermined limits. The selection of these parameters follows an established protocol for an AGC system. The proportional constant (K) is typically adjustable within the range of 0 to 0.5, while the time constant (T) can be adjusted within a range of 50 to 200 s [12]. The time constant is a crucial parameter in the secondary regulation process. It defines the speed at which the controller monitors and governs the activation of power from the participating generator. The current investigation aims to devise an AGC system that effectively provides reserve energy from a wind power plant and a flexible load system. Figure 6 prominently depicts a detailed and complex power network, illustrating the integration of power outputs from different power plant units, including thermal, gas, and wind energy. Additionally, flexible load systems are designed to actively participate in balancing operations. The solid red line signifies the flow of electricity, while the dotted line represents data exchange. Moreover, the network is interconnected with an external grid, replicating the attributes of that external grid, with a primary frequency response of 6000 MW/Hz and 16 s inertia. The following section thoroughly describes the modelling approach used for generating units. To perform the simulation analysis, the specific capacities and supplementary regulating reserves of diverse generating units and flexible loads are comprehensively expounded in Table 3. Furthermore, the abbreviations are given in Appendix A.

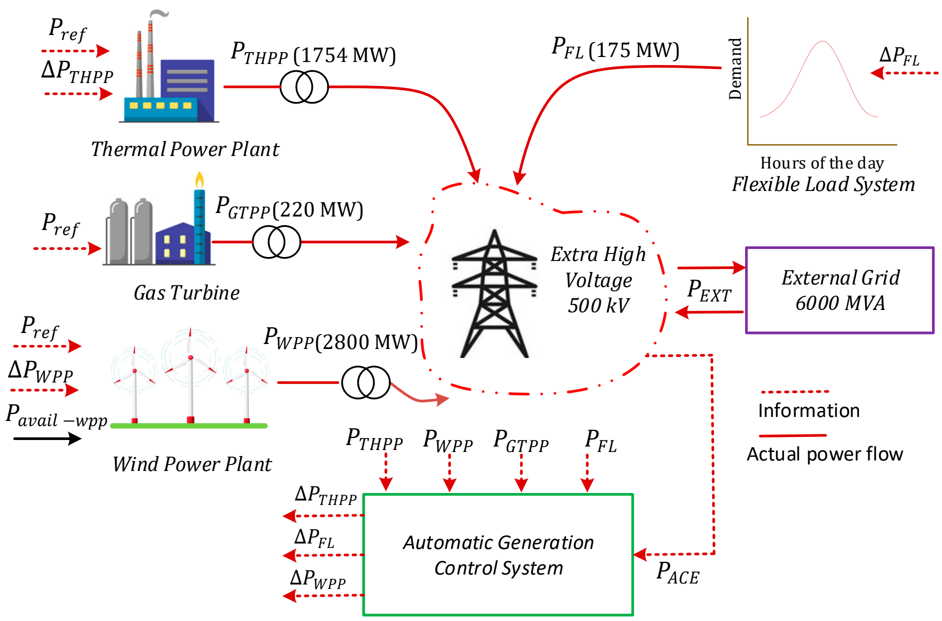

Figure 6. Proposed power system AGC model.

Table 3. Parameters of the power plant units and flexible loads (MW).

Generating Units	TPP	GPP	WPP	FLU
Power Capacities	1754	220	2800	127.5
AGC Reserves	0	0	−400	±75

4.1. Wind Power Plant System

This research study examines the dynamic behavior of wind turbines by utilizing the wind power model illustrated in Figure 7. The proposed model is instrumental in analyzing wind turbines' role in stabilizing the grid's active power control. The significance of the proposed model lies in its examination of the contribution of wind turbines to the active power control and stabilization of the grid. It incorporates the essential characteristics of a system-level wind farm, which is more critical than simply assessing the impact of an individual wind farm. This is because the collective performance of multiple wind power plants holds the utmost importance. Through this model, researchers can gain a more comprehensive understanding of the wind power plant's behavior, which is essential for effective power system analysis and control. The proposed model in this study is rooted in the IEC committee draft wind energy model for simulations on the electric level, namely IEC61400-27-1. The model is tailored and optimized for active power regulation and long-term dynamic simulation studies. By implementing these modifications, the study aims to augment its applicability in scrutinizing and comprehending the performance of wind-energy-based power plants in the realm of grid regulation and control. Figure 7 illustrates an intricate model comprising three blocks: the wind power plant active power controller (WPPAPC), the wind turbine active power controller (WTAPC), and the generator reference current block. Additionally, the frequency droop-block, which encompasses dead zone and droop features in the prototype, furnishes the fundamental frequency response (ΔP_c) that is reliant on the magnitude of available wind ($P_{WPP_{avail}}$) and the energy network's frequency droop parameters.

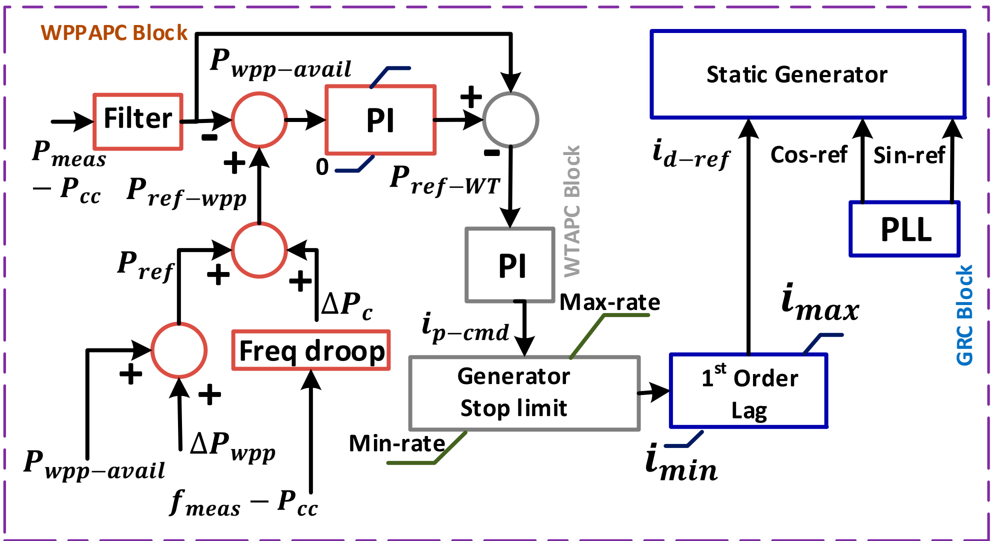

Figure 7. Wind power plant model.

The reference power (P_{ref_WT}) of the wind-energy-based power plant is generated by the WPPAPC block of the system, which calculates reference power at the power plant level (P_{ref_WPP}). At the power plant level, the P_{ref_WPP} is premeditated based on the efforts from the frequency-deviated signal (ΔP_c), input reference power signal (P_{ref}), and measured power (P_{meas_PCC}). Moreover, the difference between the P_{ref_WPP} and P_{meas_PCC} is used by the PI regulator to regulate the reference signal of the active power controller block. At the turbine level, the output signal is the active component of the current (I_{Pcmd}), which is given from the PI controller as the difference between the P_{ref_WT} and P_{meas_PCC}. This investigation has evaluated type IV wind turbine technology; these turbines possess two decoupled converters, providing enhanced operational flexibility compared to conventional turbines. The converter on the machine side governs the generator's rotation speed, whereas the grid side converges to regulate the active power flow to the grid autonomously.

In the context of the grid, this study emphasizes the converter's significance in influencing wind turbines' behavior. To facilitate a comprehensive analysis and evaluation of the wind turbine's performance under different conditions and scenarios, a static generator model based on the current source model (CSM) is utilized. This approach ensures the effective examination and assessment of the wind turbine's behavior. This approach has several advantages over other methods and is fundamental to the research methodology. Moreover, using a static generator model centered on the CSM enhances the precision and accuracy of the study's findings, which provides a more comprehensive understanding of the behavior of wind turbines concerning the grid. Further, the wind power response time to any system frequency variations falls within 2–5 s while accounting for the ramp-rate restriction imposed on the reference value. The developed wind power plant model can supply positive and negative regulatory power during power balancing. Nonetheless, operating the wind power plant at its maximum level is advisable due to its economic generation capability. On the other hand, maintaining positive reserves in the wind power plant can increase the operational cost of the system. This is because conventional power plants must provide a specific reserve amount if there are any forecasting errors. On the other hand, running wind-energy-based plants at full capacity is economically more advantageous and decreases the generated power output as required.

4.2. Thermal Power Plant System

This study analyzes the active power control aptitude of a thermal power plant model in the frequency regulation procedure of the grid. The model is designed with primary and secondary control capabilities. Figure 8 illustrates a comprehensive model diagram derived from the literature [31,32] and is streamlined for long-term dynamic studies. The turbine out on the mechanical side, represented as P_{mech}, is derived from the output control valve (cv) of the governor block and the steam pressure (P_t) of the boiler block.

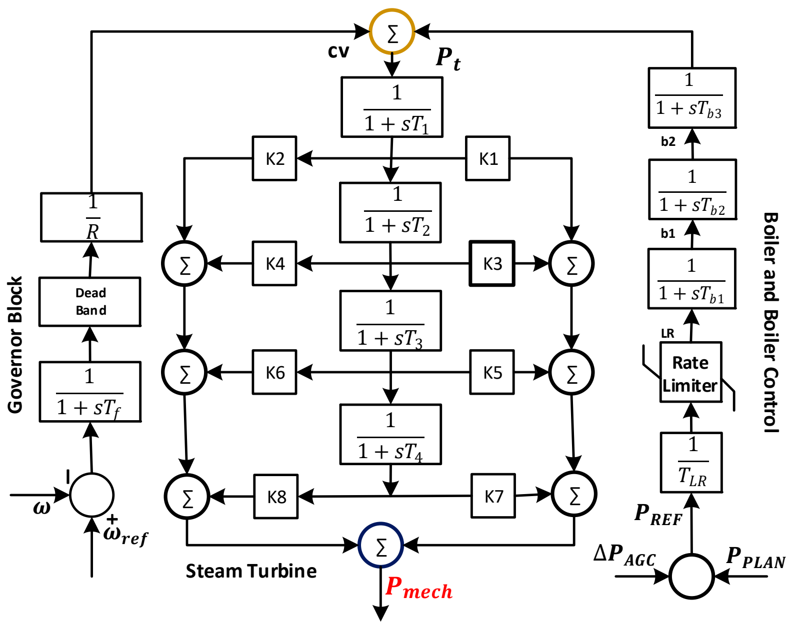

Figure 8. Thermal power plant system.

The reference load signal compensates for changes in the load (L_R) and transmits the necessary information to the boiler block to calculate a new value of steam pressure (P_t). The updated steam pressure value is computed by considering the operational restrictions of the turbine and the delays related to the steam energy stored in the boiler. Moreover, the GRC (governor rate constraint) and STC (steam turbine constraint) effects are also incorporated into the model, which maintains the ramp-rate limit at 30 MW/min. The speed governor provides a primary response by taking the input of speed deviation and taking into account the droop setting of the turbine. Dead bands are integrated into the model to prevent the governor valve from responding to minor fluctuations caused by mechanical faults.

4.3. Gas Turbine Power Plant

The study has incorporated a composite power plant model based on a gas turbine, intended mainly to provide the primary frequency response via installed governors. The model includes a dead band and low-pass filter to prevent harm to the turbine caused by minor fluctuations. Using the frequency droop feature of the turbine and the frequency deviation signal, the power plant generates a power demand signal (ΔP_c) that functions as an input to the power plant. The power plant model has three components: a power distribution block, a power limitation block, and the gas turbine dynamics, as shown in Figure 9.

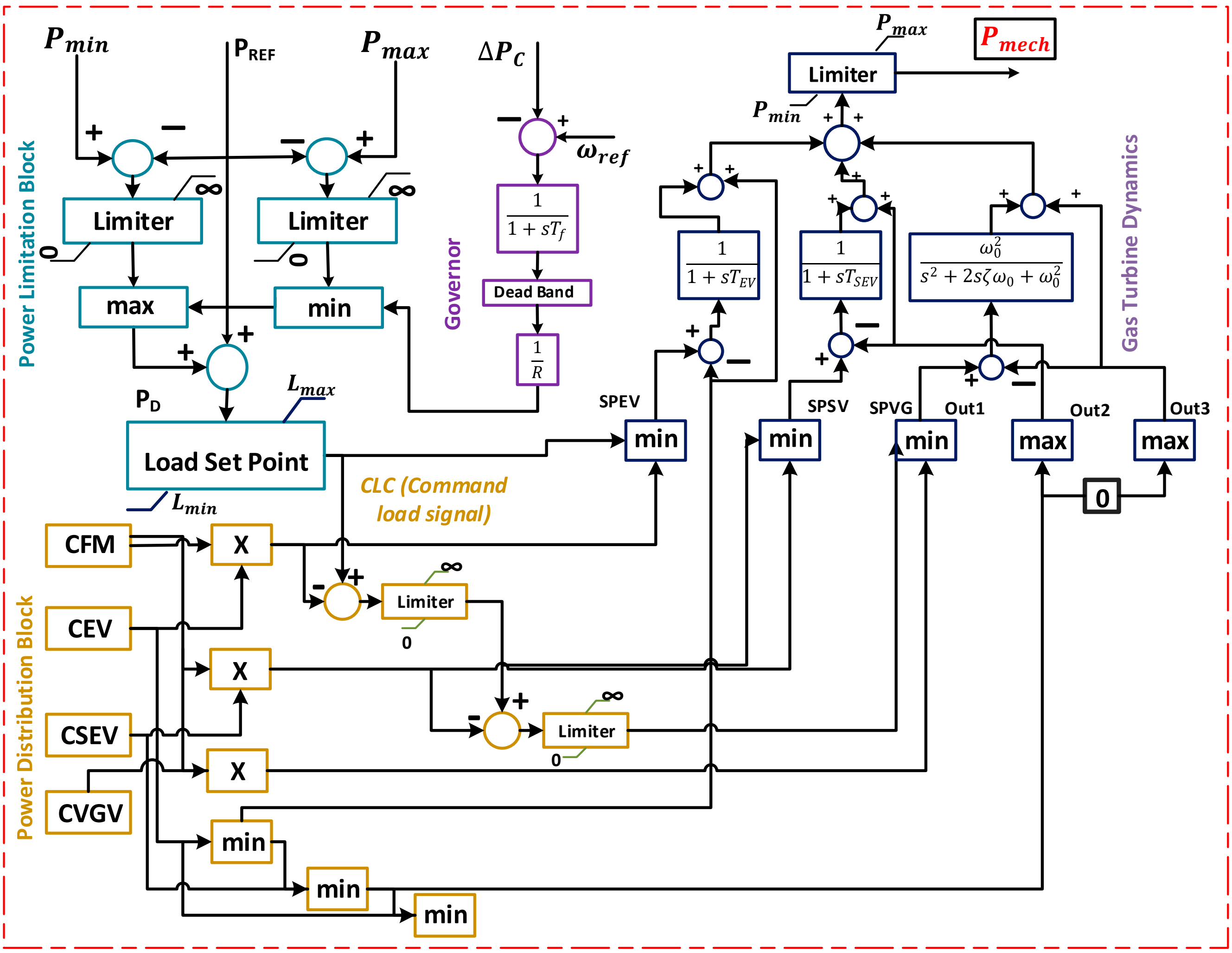

Figure 9. Gas turbine power plant system.

The distribution block restricts the response of the turbine by imposing two limits, P_{max} and P_{min}, on the reference power signal, using the physical limits of the combustion technology. The distribution block creates a command load signal that is then employed as input to the power limitation block, which contains combustion chambers firing in series. The overall mechanical output of the turbine (P_{mech}) is confined to the maximum and minimum power levels and depends on various signals, including CSEV, CVGV, CLC, CEV, and CFM. The gas turbine's reaction time to any modification in the system frequency line encompasses a time frame of 25–30 s, while also factoring in the related delays and constraints on ramp rate.

4.4. Flexible Load Design

This aforementioned study has provided detailed insights into the complex configurations of electric vehicles and cold storage units, which serve as flexible loads capable of offering a secondary response in power balancing operations, specifically in an AGC system. The theoretical equations pertaining to flexible loads and their role in providing frequency ancillary services are extensively presented. The research assumes that in Pakistan's future power system, numerous cold storage units will be capable of providing an adequate response during power system balancing operations. Therefore, the study incorporates the cold storage unit as a flexible load within the integrated model, with a regulation capacity of $\pm$127.5 MW.

4.5. Proposed AGC Dispatch Strategy

This study presents a simulation of the AGC unit for the future Pakistan power system, which allows the wind power and the cold storage units to participate in the frequency regulation services of the grid. The formulated dispatch strategy is presented in Figure 10 and is based on the principle of cost optimization. It is perceptible from the diagram that in the event of any alteration in the system frequency, the wind power plant and cold storage unit are tapped to utilize the available reserves. However, it can be seen that wind power is operated at its maximum capacity and only provides its service during a negative regulation process when the frequency rises from its nominal value. The rationale is that the operational costs related to positive power regulation increase, given that the retained reserve power from wind power plants must be sourced from alternative generating units or imported from external power systems in case of any forecasting inaccuracies. Moreover, the wind power plant represents a minimum incremental cost compared to the traditional generating units and is recommended to be operated at maximum capacity. Conversely, if it is required to reduce excess power, power from the wind power plant can be curtailed quickly for the regulation service. However, cold storage units are a flexible load system for affirmative and opposing regulation amenities. In scenarios where affirmative regulation is sought, the flexible load offers an immediate reaction at a velocity stipulated by the system's inertia. The response from the flexible loads is continued until all the reserves are depleted and the ΔP_{FL} touches its lower limit.

The dispatch strategy designed for this purpose is depicted in Figure 10 and is based on a cost optimization strategy. From Figure 10, any alteration in the system frequency will result in using reserves from the wind power plant and the cold storage unit. However, the wind power plant always operates at maximum capacity and provides service during negative regulation when the frequency exceeds its nominal value. The underlying principle is that operational expenses amplify when reserve power from wind power plants is secured from alternate generating units or imported from other power systems in case of inaccurate forecasts.

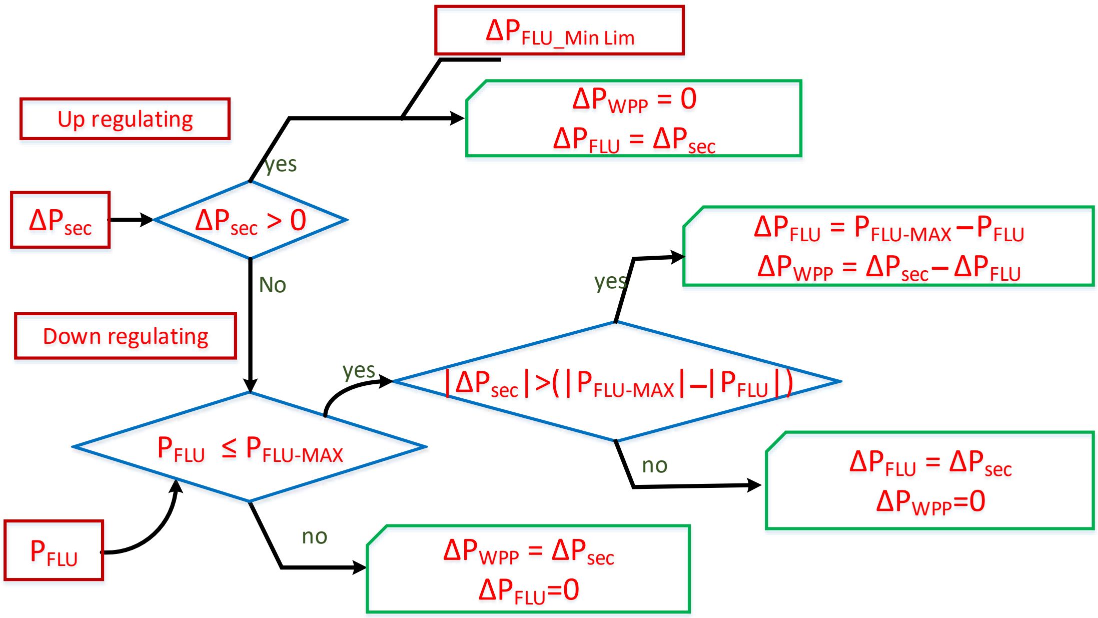

Figure 10. Proposed dispatch strategy.

Moreover, wind power plants have a lower minimum incremental cost than traditional generating units and are thus recommended to be operated at maximum capacity. Conversely, when required to reduce excess power, wind energy can be easily curtailed for the regulation service. On the other hand, the cold storage units, serving as a flexible load system, are utilized for both positive and negative services. In the case of a power deficit, the flexible load system provides a rapid response at a rate specified by the system's inertia. The reaction from the flexible load continues until all reserves are depleted, and the ΔP_{FL} reaches its lower limit. Flexible load units take the lead in responding when there is a surplus of power or negative regulation. Wind power plants are only scaled down when the reserve power from flexible load units reaches the maximum of ±127.5 MW, as it is cost-effective to operate them at full capacity. Equations (21) through (27) comprise the positive and negative regulation equations.

1. Positive Regulation Dispatch

$$\Delta P \geq 0\,(\text{Power Deficit}) \tag{21}$$

$$\Delta P_s = \Delta P_{FL} \tag{22}$$

Subject to

$$\Delta P_{FL} > \Delta P_{FL-minlim} \tag{23}$$

2. Negative Regulation Dispatch

$$\Delta P < 0\,(\text{Power Excess}) \tag{24}$$

$$\Delta P_s = \Delta P_{WP} + \Delta P_{FL} \tag{25}$$

Subject to

$$\Delta P_{WP} > \Delta P_{WP-minlim} \tag{26}$$

$$\Delta P_{FL} < \Delta P_{FL-maxlim} \tag{27}$$

4.6. Results and Discussion

Ensuring the security and stability of the electrical grid relies on maintaining a balance of power, which is crucial for an uninterrupted power supply. Managing the grid's active power is mainly achieved through secondary regulation provided by AGC. This research has designed an AGC system for the future Pakistan power model incorporating reserve power from conventional and renewable energy sources. The model integrates various power sources, including thermal power systems, gas turbines, wind power plants, and flexible load systems, as shown in Figure 6. However, secondary reserves are only available from wind power plants and flexible load systems, according to the dispatch strategy in Figure 10. Figure 11a illustrates the 24 h power generation on a high windy day, showing the variable generation pattern of thermal and wind power plants. In contrast, the gas turbine's power generation remains at 220 MW.

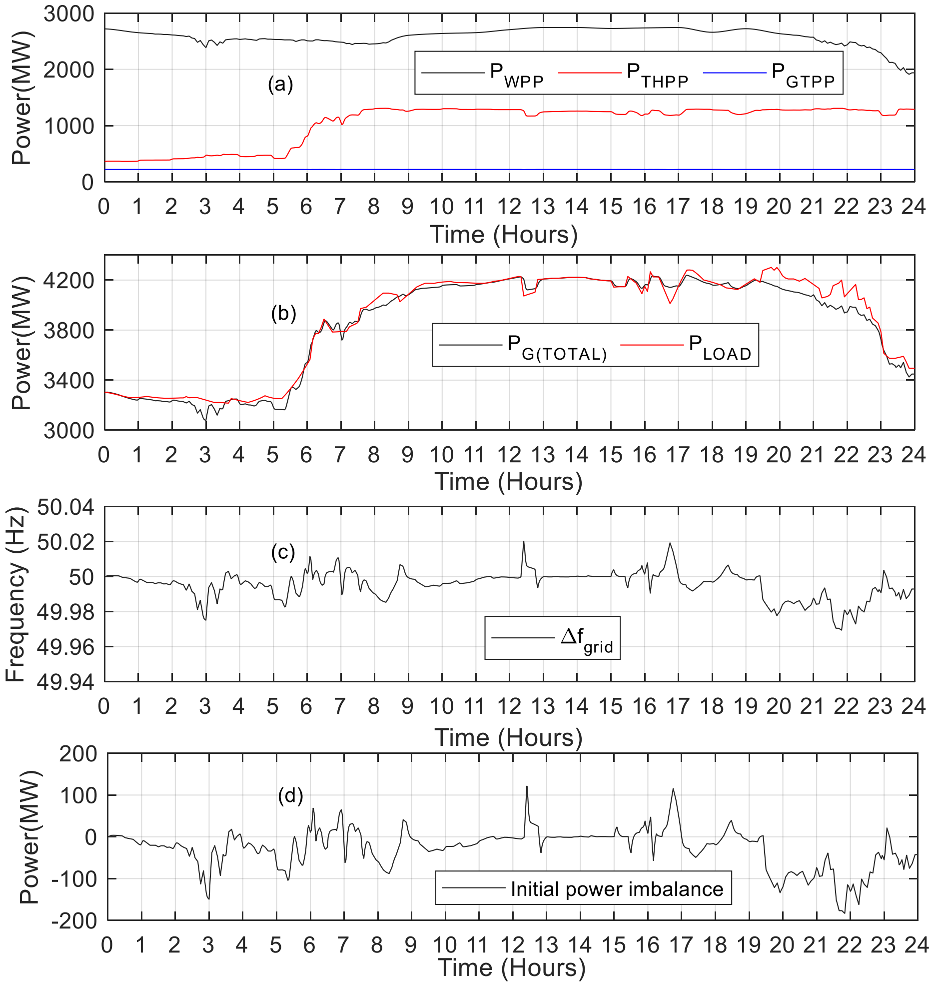

Figure 11. (**a**) Individual generation. (**b**) Load demand and net generation. (**c**) Grid frequency pattern. (**d**) Initial power imbalances.

It is important to highlight that wind energy is inherently associated with forecast errors, leading to discrepancies between the input values utilized in load-generation balance calculations and the actual values. Consequently, in addition to load demand fluctuations, the inconsistency between the actual and predicted values of wind power plants causes real-time power imbalances between supply and demand. Figure 11b shows the accumulated generation from the different sources and the net load demand. Observing the illustration, it is apparent how the difference in net generation and load demand causes a gap in the system frequency. This emphasizes the necessity of immediate action to resolve power imbalances since they might negatively affect the stability and dependability of grids. The AGC system takes immediate action and controls the output of the generating units participating in the AGC services. Figure 11d illustrates the real-time power imbalances that must be minimized to maintain the stability and reliability of the electrical grid. This work alleviates these discrepancies through the AGC system, which incites reserves from the wind power plant and the flexible load system. It is worth noting that the flexible load system's maximum limit of ±75 MW is considered in this study. At the same time, the wind power plant is only utilized for AGC services when the grid frequency surpasses the standard level. This approach is supported by the dynamic algorithm incorporated within the proposed AGC system, which optimizes the operation of the regulating reserves to sustain the electrical grid's balanced state.

In the case of a power system asymmetry, the frequency signal of the system undergoes fluctuations and deviates from the nominal level. The governors at power generation units detect these frequency variations and promptly activate the frequency containment reserves (FCRs) essential to maintaining power system stability and reliability by arresting the frequency deviations at that instant. The governors engage the FCRs to promptly modify the frequency deviation to a new stable state level within a few seconds in response to a power system imbalance. The swift activation of FCR helps to ensure that the frequency deviations remain within acceptable limits, preventing potential damage to power system equipment. After the system frequency is fine-tuned to a new steady-state level with the aid of FCRs, supplementary reserves are activated to return the system frequency to its initial state. Deploying secondary reserves also releases the FCR reserves, which typically operate on minute timescales. Secondary reserves ensure the power system returns to its original state and maintains the desired frequency output.

The proposed AGC system in this study is formulated to regulate the system frequency using wind power and flexible load participation. The AGC system and the ACE employ this data to evaluate the power dispatch from the generating units and the flexible load systems. Additionally, the dispatch strategy of the AGC system tackles various issues in power system operation, such as practical operational constraints (e.g., dead bands, delays), power curtailment problems, and parameter uncertainties related to wind power. As an outcome, it is a proficient resolution to diminish the reserve usage from traditional power-producing units. Meanwhile, it presents a remedy for wind-energy-based systems with high integration by curtailing operation costs.

As presented in Table 2, the system load and all generating units are simulated, and parameters are defined to determine their operational characteristics. The primary response in the system is provided by the wind, thermal, and gas power plants, while the AGC response is exclusively acquired from the wind-energy-based power plant and flexible load units. It is hypothesized that the flexible consumption unit could regulate within the range of ±75 MW via AGC without impeding its primary function. Figure 11d displays the initial power imbalances that necessitated the activation of reserves from the FLUs and wind power plant through the AGC mechanism using the designed dispatch strategy. The process of dispatching the AGC reserves, as revealed in Figure 10, is based on the cost optimization technique, which minimizes operational costs while ensuring that reserve utilization from conventional generating units is limited.

Initially, the deviation between the actual and nominal frequency resulted in an error in P_{ACE}, which is then rectified by activating the secondary reserves of power plant units through the AGC system. The suggested dispatch strategy divides the secondary response obligation between the wind power plant and the FLUs. Additionally, it can be observed from Figure 12b that the FLUs are utilized in both generation excess and generation deficit conditions. At the same time, the wind power plant is exclusively subject to regulation for generation excess. Additionally, the figure highlights that the wind power plant reduces its energy production only after all the secondary reserves of the FLUs are exhausted, thereby allowing the wind power plant to operate at its maximum capacity.

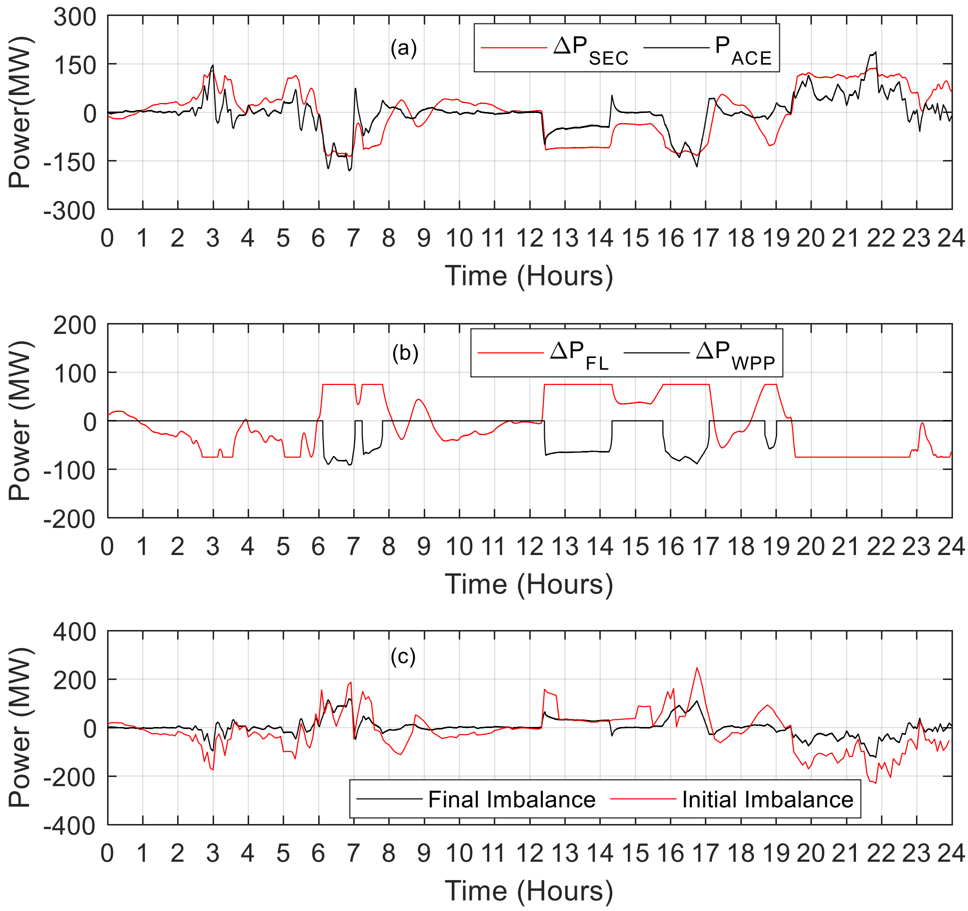

Figure 12. (**a**) AGC response following ACE. (**b**) Power dispatch (WPP and FLU). (**c**) Error comparison following AGC response.

The grid frequency following the AGC response is given in Figure 13. Further, to comprehensively evaluate reserve usage from wind power plants and FLUs, the AGC system was triggered to activate 1.4 GWh of energy from WPPs in over-generation and under-generation cases. Furthermore, 0.699 GWh of energy was obtained from FLUs without negatively impacting their primary functions. Failure to utilize these wind and load reserves would necessitate a significant reliance on traditional power plant reserves to accommodate active power imbalances in a wind-power-integrated power system. This would not only elevate operating expenses but also increase C02 emissions.

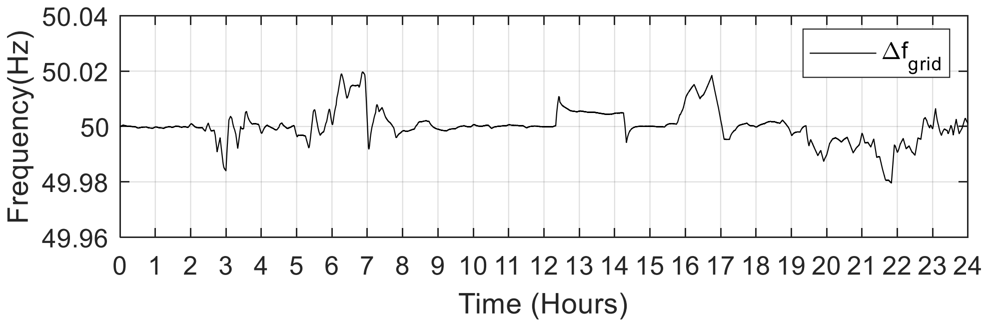

Figure 13. Grid frequency with AGC.

5. Conclusions and Future Work

The growing penetration of renewable energy sources in conventional power systems has increased the demand for reserve power due to the associated forecasting errors. To ensure a real-time balance between load and generation while minimizing the need for reserve power, wind farms are interested in participating in AGC services, especially when organized into regulation zones with different technology-based generation units. Additionally, flexible loads such as electric vehicles and thermostatically controlled loads play a significant role in the modern power system as grid ancillary service providers through AGC. Hence, analyzing control strategies at different levels that integrate reserve power from flexible loads is imperative. This study has extensively reviewed the fundamental concepts of wind farms and flexible loads and emphasized their contribution to load frequency control, a critical function of AGC. An extensive review of current and past AGC practices integrating reserve power from wind power and flexible loads (EVs and TCLs) was then presented. Subsequently, a real-time dynamic dispatch strategy to integrate reserve power from wind farms and flexible load units was proposed for the developed model of the AGC system. A future Pakistan power system was created in DIgSILENT PowerFactory software 2020 SP3 to implement the proposed control strategy, which integrated thermal power plants, gas turbines, wind power plants, and flexible load units. The outcomes revealed that using reserve power from wind and flexible loads can effectively reduce power imbalances while maintaining the security of the power system. Furthermore, it decreased reliance on traditional sources and improved the system's economic performance.

In the future, there exists a possibility to expand the scope of work towards investigating the potential of combining solar and wind farms for providing frequency support services to power grids. This could prove to be an effective solution for enhancing the stability and reliability of the grid system. Additionally, innovative AGC system control approaches can be designed using advanced AI technology. Such approaches would enable more precise forecasting of various grid parameters, thereby mitigating errors and enhancing the system's overall performance.

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Nomenclature

P_{ij}^{Act}	Actual power in the interchange line
β_k	Bias factor for the ACE
P_{ij}^{Sch}	Reference power in the interchange line
ΔP_s	Required secondary dispatch
ΔP_{WP}	Secondary dispatch from wind power plant
ΔP_{FL}	Secondary dispatch from flexible load unit
I_{Pcmd}	Static generator current
ΔP_{ref-Gi}	Load reference signal of ith generator
$P_{ACE,k}$	Area control error of the kth area
ΔP_{Gk}	Dispatch power from the K^{th} generator

Appendix A

Acronym	Definition	Acronym	Definition
AGC	Automatic generation control	PLB	Power limitation block
PJM	Regional transmission company	GTDB	Gas turbine dynamics block
TPP	Thermal power plant	CLC	Command load signal
GPP	Gas turbine power plant	SEV	Sequential environmental combustion
CESs	Capacitive energy storage system	CSEV	Sequential environmental burner capacity
BESs	Battery energy storage system	CVGV	Variable inlet guide vane position compressor capacity
STC	Steam temperature control	CFM	Baseload function
PRR	Positive regulation reserve	NRR	Negative regulation reserve
V2G	Vehicle to grid	SMA	Smart management approach

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