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# Ancillary services from wind and solar energy in modern power grids: A comprehensive review and simulation study

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## ABSTRACT

Renewable energy sources like wind and solar have increased demand for surplus power capacity. The demand is primarily fueled by the growing impact of forecasting errors associated with these intermittent energy sources. Implementing advanced control methods for automatic generation control (AGC) is essential to integrate wind and solar power with conventional generation sources to balance the power system and reduce reliance on traditional reserves. Therefore, this paper comprehensively overviews solar and wind energy integration in the AGC framework to provide optimal grid ancillary services. Initially, the paper presents an overview of the basic equations used to integrate reserve power from the photovoltaic (PV) system by employing the de-loading strategy. Subsequently, a comprehensive review is conducted on integrating the PV system in AGC strategies to provide grid ancillary services. The study also analyzes the contribution of wind power in AGC services using relevant equations and past practices. The paper presents a real-time dynamic control strategy to optimize the dispatch of the AGC unit by integrating the operating reserves from wind energy systems in conjunction with thermal power systems. The study simulates an 8-bus, 5-machine model using the Dig-SILENT Power Factory. The findings reveal that utilizing operating reserves from wind power can significantly reduce large-scale forecasting errors in massively renewable energy resources (RES) integrated power systems, thereby ensuring the necessary system operational security and reducing the reliance on traditional generating units.



## I. INTRODUCTION

Renewable energy technologies, such as wind and solar energy, are experiencing an expected expansion and are increasingly integrating into large-scale power systems to diminish reliance on fossil fuels, combat climate change, and establish sustainable energy solutions. Wind power, for instance, has established itself as an extensively deployed renewable energy source. Onshore and offshore wind farms, consisting of multiple wind turbines, are undergoing rapid construction and development. Technological progress has dramatically improved turbines' efficiency, increasing power generation, and reducing costs. Innovative designs and complex structures allow turbines to capture stronger and more consistent winds, leading to better energy production optimization.[1] Similarly, there has been significant growth and progress in solar energy. Developments in PV cell technology have substantially enhanced conversion efficiency, enabling solar panels to yield more substantial amounts of electricity from a given quantum of sunlight. Further, integrating solar panels into diverse structures, including rooftops and solar farms, has broadened their deployment potential. As solar power becomes cost-effective, it is pivotal in diversifying energy sources within power systems.[2] However, the inherent intermittency of solar and wind energy can significantly impact the system's operational performance, which results in forecasting issues and generates a power gap between supply and demand.

Power grid operators utilize various scheduling approaches to address the forecasting issues during power balancing operations. These methods mostly rely on utilizing surplus energy from traditional power plants, which has serious cost consequences and compromises the system's overall stability.[3,4] In order to properly solve this issue, it is imperative to utilize solar and wind energy's capacity to supply system services while preserving load and demand equilibrium. In the power system, frequency stability directly relates to the balance between supply and demand for energy. Significant damage and extensive service outages can arise from even small frequency variations. Therefore, it is imperative to implement a robust control system that can ensure stability over the long term. To accomplish this, an advanced multi-tiered control system is implemented, which includes several levels of control and regulation. This comprehensive system is designed to properly monitor and control the whole frequency spectrum, reducing the risk of interruptions and ensuring consistent service delivery.

Every level operates on distinct timeframes, working together to improve the overall frequency regulation and the reliability of the system operation.[5] In this context, automatic generation control (AGC) plays an essential role in maintaining power balance and ensuring stability in the system frequency.[6] AGC functions operate on a minute-level timescale, monitoring and fine-tuning power generation to oversee the system's frequency effectively and ensure its regulation.[7] Conventionally, AGC relies on reserves drawn from traditional energy sources. However, the massive integration of solar and wind energy introduces considerable forecasting errors, leading to fluctuations in the system's frequency, which can adversely affect the system's secure operation.[8] Further, this power insufficiency is addressed using reserves from traditional energy systems, thus increasing the operational cost of the system operation. Therefore, exploring the capacity of renewable energy resources, particularly wind and solar power facilities, is imperative to actively participate in AGC services.[9,10]

In recent years, significant research has focused on the operation of AGC systems, particularly concerning the integration of wind and solar energy into the current power system framework. In this context, AGC operations effectively utilize and optimize power reserves from renewable sources in conjunction with conventional energy sources.[11–13] For example, the authors in Ref. 11 evaluated an 800 kW wind turbine in Saskatchewan, Canada, to assess its effectiveness in providing secondary frequency response as a part of the AGC system. Wind turbines' technical capacities and limitations in providing such response services were discussed. The outcomes presented 59% and 65% performance ratings when utilizing the PJM methodology for wind speeds surpassing and dropping below the designated threshold. Despite these relatively satisfactory scores,[14] successfully demonstrated the profitability of incorporating wind power into the regulation market. Moreover, the promising potential for enhancing the regulation of wind power by ensuring an ample supply of wind energy and a study of the precise tracking of power command signals derived from the AGC system is presented. In Ref. 15, the authors extensively examined a power grid model incorporating a substantial proportion of wind energy and assessed the effectiveness of supplementary services offered by wind power facilities within a simplified yet significant context. The findings revealed that guaranteeing the reliability of modern power systems with a substantial integration of wind power requires synchronization between wind energy systems and conventional energy resources.

Similarly, solar power is the most prevalent and user-friendly form of renewable energy resources.[16–18] The authors in Ref. 18 examined the effect of PV generation on the load frequency controller. The analysis revealed that incorporating a 10% PV source into the grid would demand a proportional increase of roughly 2.5% in the capacity of the AGC, surpassing traditional AGC controllers. In Ref. 19, an AGC technique is presented for a power grid comprising multiple integrated areas and incorporating PV generation sources for ancillary services. This methodology addressed the challenge posed by the nonlinearities in the generation rate constant and the dead band by establishing a discrete-time state-space model. Subsequently, it involved the creation of a predictive model utilizing the state vector and applying the control signal roll optimization technique. Furthermore, a comprehensive comparative assessment of the proposed control models, when compared with heuristic models based on GA, FAA, and PSO algorithms, provided compelling evidence for the superiority of the implemented approach. The ability of AGC to manage the intermittent performance of PV modules is illustrated in Ref. 20, which relies on isolated data obtained from various locations. Additionally, the study suggests that AGC's effectiveness depends on the intermittency rate. In cases where it is assumed that a specific power plant will mitigate PV fluctuations, the necessary AGC capacity surpasses that of the PV system. Moreover, the study has mentioned that the monitored insulation levels at a single point significantly impact the efficacy of AGC.

The literature discussed above highlights that the ability of the PV and wind energy systems to deliver AGC services depends on the design of control technologies and turbine and inverter technologies. Therefore, conducting a comprehensive analysis of various technologies and their associated control mechanisms in the PV and wind energy-based AGC system is important to facilitate the smooth provision of frequency support services in power grids. This study offers a comprehensive approach to understanding and exploring existing control strategies for integrating the operating reserves from photovoltaic and wind energy sources. Initially, the study reviews the fundamentals of AGC operation for PV systems, focusing on the de-loading strategy, followed by a detailed literature survey. Similarly, the study examines the operation of type 4 wind turbines for AGC in large-scale wind energy-based power systems, followed by an in-depth overview of various AGC models for wind energy, incorporating different control methodologies, including intelligent and model predictive control techniques. It also explores their integration with components such as Flexible Alternating Current Transmission Systems (FACTS) and energy storage devices. Finally, the study presents a dynamic and real-time power dispatch strategy for the AGC system, integrating reserve power from wind and thermal energy systems. An eight-bus, five-machine model was developed, incorporating generating units from wind, thermal, and gas turbine-based energy systems. The developed AGC model was tested to mitigate forecasting errors in the power system induced by wind power plants by incorporating reserve power from the wind energy system alongside the thermal energy system. The results revealed that integrating renewable energy systems into the AGC operation substantially reduces the utilization of reserves from the thermal energy system while simultaneously enhancing the economic operation of the system.

The main contributions of the paper are as follows:

- A dynamic model of the PV-based AGC system is reviewed, providing a comprehensive explanation of the fundamental equation for integrating PV systems into AGC services using a de-loading approach. This section also comprehensively reviews various control techniques to incorporate PV systems into the AGC models.
- The wind energy contributions to AGC services are reviewed, specifically considering type IV wind turbine technology. Further, considering intelligent, modern, and predictive control approaches, a thorough assessment is conducted on diverse wind energy systems to deliver frequency ancillary services. The study investigates how wind power contributes to AGC services when combined with FACTS devices and energy storage systems.
- The study presents a case study in which a real-time dynamic power dispatch study is developed for the AGC system to integrate the results from the wind and thermal energy systems in power balancing operations. An eight-bus, five-machine model has been developed for the simulation analysis, which accurately represents the complexities of the power grid, incorporating the generating units of wind turbines, thermal power plants, and gas turbines.

The paper is organized as follows: Section II presents the role of solar PV systems in AGC services, illustrating the equations related to the de-loading concept. Section III outlines the fundamental formulas for wind power integration in AGC systems, followed by a detailed literature review of different control schemes. In Sec. IV, the developed power grid model incorporating the AGC system has been presented. In Sec. IV D, the study introduces the proposed dispatch strategy for the AGC system, while Sec. IV E analyzes and discusses the results. Finally, Sec. V provides a conclusion summarizing the findings and future work.

## II. PHOTOVOLTAIC POWER (PV-P) CONTRIBUTION IN AUTOMATIC GENERATION CONTROL

### A. System overview

The global share of solar power and the installed capacity of solar generating stations have witnessed significant growth to meet the overall power demand and the adverse environmental impact. PV system, itself, is a non-inertial source. However, the proper integration of large-scale solar energy while maintaining grid stability and dependability is made possible by strong system inertia, effective grid management, and a variety of generating sources. The net power of the photovoltaic system, represented as $P_{pv}$, is influenced by several elements, such as panel efficiency ($\eta_{pv}$), ambient temperature ($T_a$), sun irradiation (I), and panel size $A_{pv}$. The following is an expression of this relationship:

$$P_{pv} = \eta_{pv} A_{pv} \mathbf{I}(1 - 0.0005(T_a - 25)). \quad (1)$$

The incorporation of PV systems into AGC units represents a significant step forward in the pursuit of a more resilient and environmentally friendly electricity grid. Through the use of accurate forecasting methods, effective power dispatch strategies, and integration of solar power generation, the AGC system can enhance grid stability and boost the penetration of renewable energy sources. In this process, the AGC algorithm plays a crucial role in tuning power dispatch and controlling the system. The availability of solar irradiance, grid constraints, and system stability are only a few of the variables that the AGC algorithm takes into account while dynamically adjusting the generating set points for solar PV systems. Adopting such a robust control mechanism results in a more stabilized grid with large-scale renewable energy sources. Frequency control is overseen within PV systems using a de-loading approach.[21,22] In this approach, the PV array is operated at a distance from its maximum power point tracking (MPPT), allowing surplus power to be stored autonomously within the PV system. These reserve power can be utilized whenever there is a need for increased generation, thus preventing frequency interferences. Therefore, in scenarios where PV relies upon frequency control, it is assumed that the PV panel is deliberately de-loaded by a pre-determined percentage of the maximum power to ensure an adequate reserve is available for immediate utilization. As discussed, a pivotal element in this frequency control scheme is the elevation of the PV voltage, denoted as $V_{PV}$, surpassing the voltage at the maximum power point $V_{mpp}$. By changing $V_{mpp}$ with an increment known as $V_{deload}$, the PV array retains a reserve of power. This reserve power resource comes into play when deviations in system frequency transpire. In such instances, the DC reference voltage $V_{dc}$ is modified by an added control signal in proportion to the frequency deviation, symbolized as $V_{dc}\Delta f$. The PV output power relies not only on $V_{mpp}$, but also on the strength of the frequency deviating signal as shown in the following equation:

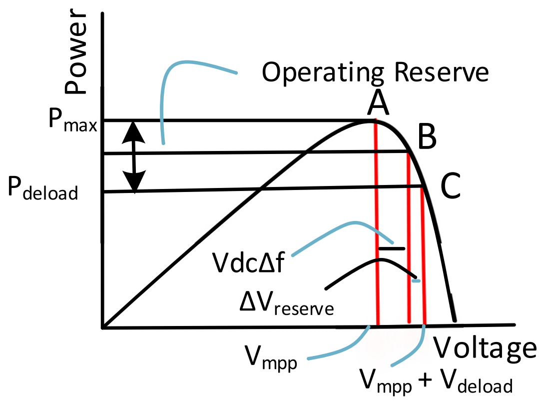
$$V_{deload,ref} = V_{mpp} + V_{deload} - V_{dc,ref}. \quad (2)$$

The operational dynamics of the de-loading scheme are depicted in Fig. 1(a), illustrating the PV system's operation at point C to accumulate a surplus power reserve. Sustaining this configuration continues until the control signal, predicated on the frequency deviation, initiates a reduction in the PV voltage, thereby compelling the system to transition to point B. Nonetheless, a notable drawback of this approach is the sub-optimal utilization of all PV units for the frequency control system. This limitation is effectively tackled by enhancing the controller through the incorporation of a control signal that considers the remaining reserve power of the PV units, symbolized as $\Delta V_{reserve}$, as visually illustrated in Fig. 1(b). Consequently, this modification in Eq. (2) has resulted in the following equation:

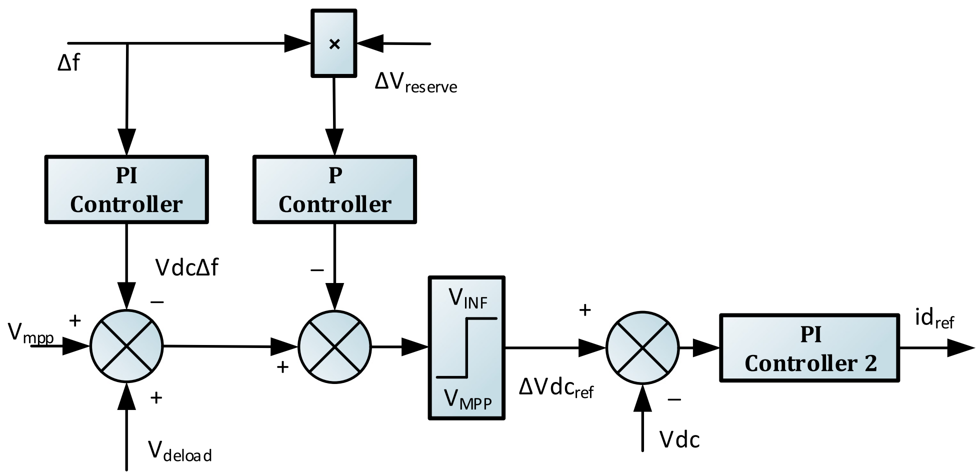
$$V_{dc,ref} = (V_{mpp} + V_{deload} - V_{dc}\Delta f) - (\Delta f \times \Delta V_{reserve} \times k_{p2}). \quad (3)$$

### B. Literature on PV integration in AGC services

Recent research indicated a growing interest in improving frequency support using PV systems. The primary focus was incorporating energy storage systems (ESS) into power grid frequency controllers. However, this approach demands significant investment,




(a)




(b)

**FIG. 1.** (a) PV system regulation using de-loading strategy. (b) Modified de-loading strategy-based PV systems.

and the lifespan of ESS is shorter compared to PV system components.[23] Consequently, an alternative frequency control strategy involving the reduction of the PV generation output utilizing the inherent capabilities of the PV system could be explored to avoid additional investment. A de-loaded PV system was implemented to provide frequency support in a multi-bus large-scale PV system.[24] The trial configuration comprised two traditional generators and twelve PV installations. The researchers also evaluated by comparing the de-loaded solar PV facility against a battery ESS, specifically targeting frequency support services. The de-loaded solar PV system proved more cost-effective than the ESS model for frequency support.[24] Moreover, Ref. 25 discussed recent research on using solar PV systems to regulate system frequency like conventional units. The research study encompasses a concise overview of solar PV energy systems, the significance of power electronic converters with renewable energy sources, challenges in integrating renewable-based electricity into the grid, and various approaches for achieving frequency regulation capability from solar PV systems. The authors of Ref. 26 examined the AGC difficulties in wind- and solar-powered power grids, taking into account elements such poor system inertia and forecasting problems. Additionally, an artificial intelligence algorithm is created to supply operational reserves from solar energy sources to the FO-PID of the AGC system.

Moreover, research is conducted to develop an efficient PV model for operating under the AGC system without the support of ESS. In this regard, the authors in Ref. 16 introduced an innovative method for active power control designed for a solar system lacking a battery energy storage setup, mainly designed for AGC objectives. The process utilizes a neural network estimator technique with an improved perturb and observe approach, significantly enhancing the system's dynamic performance considering various disturbances, including temperature variations, non-uniform irradiance, and load fluctuations. The utilization of these control approaches enhances the resilient operation of the system and greatly impacts the reduction in the $Co_2$ emission. The first level of response is the inertial frequency response, which has been studied by the researchers in Ref. 17 and controls the frequency in large scale grids integrated with solar energy systems.

This technique associated drawback related to the imposition of constraints on the level of the capacity, which has affected the performance of the system operation to handle the large-scale fluctuation. In Ref. 18, a mathematical model was given to evaluate the LFC/AGC capacity in the presence of solar plants integrated into a conventional power system. The study discovered that when solar plants contribute 10% of the entire power output, an additional 2.5% LFC is required compared to a standard power system without solar integration. This suggests that the existence of solar plants creates new dynamics that demand changes to the LFC approach to assure power system security.

The study[23] developed a novel active power management approach particularly built for PV inverters to contribute to frequency regulation services, taking into account the intrinsic nonlinear features of PV arrays. This approach aimed to achieve high precision and quick reaction in managing the solar system's net output power. By tackling the nonlinearity inherent in PV arrays, the suggested approach enabled accurate control of active power generation, enabling maximum performance and efficiency under diverse operating situations. In Ref. 27, the authors fully examined modern solar MPPT approaches, focusing the performance evaluation of these techniques under both solar irradiance circumstances. The assessment criteria included real-world application costs, dependence on solar photovoltaic (SPV) array characteristics, training requirements, circuitry complexity, MPPT tracking speed, number of sensed constraints, and overall efficiency. However, during operation at the MPPT, the PV system attains its optimal performance, with the DC bus voltage reaching $\boldsymbol{V_{mpp}}$ and the power output peaking as $\boldsymbol{P_{mpp}}$. The impact of operation at a higher voltage ($\Delta$V) beyond $\boldsymbol{V_{mpp}}$ results in a reduced power output denoted as $P_1$. This condition indicates that the PV system operates in a loaded state, failing to harness the complete available power. The disparity between $P_1$ and $\boldsymbol{P_{mpp}}$ represents the reserve power, referred to as preserve, which holds the potential to be utilized for frequency control.[24] All the aforementioned research studies are summarized in Table I.

## III. WIND ENERGY CONTRIBUTION TO AGC SERVICES

### A. System overview

The proliferation of wind-based energy systems posed a transformative shift in the landscape of bulk power systems, thereby significantly influencing the security and reliability of system operations. This paradigm shift stems from the inherent intermittency characterizing wind-based energy supply, a characteristic that necessitates innovative strategies to ensure continuous integration with existing power infrastructures. Within power system operations, the imperative to effectively harness the potential of wind power has prompted the development and application of two primary approaches to leverage the regulation capabilities of wind-based energy sources.[28] These approaches, namely, the pitch angle and rotor adjustment techniques, are pivotal in managing the dynamic nature of wind power injection and enhancing the stability of large-scale grids.[29] Pitch angle-based strategies focus on adjusting wind turbine blade behavior in real time to optimize power output. Conversely, rotor control speed techniques involve changing the rotational speed of turbine blades.[12] When considering an isolated wind turbine, the adjustments in load power are intelligently distributed among the turbines within the wind farm, ensuring stable system frequency. This task is executed by considering the well-defined parameters of a PI controller, a fundamental component of control systems. AGC's participation factor also measures each turbine's contribution to the overall system dynamics and helps allocate regulatory responsibilities.[30] However, determining the most beneficial dispatch factor for the AGC involves a detailed examination of various aspects, such as wind turbine speed changes, backup capabilities, deployment limits, and wind energy production costs.[31,32]

To present a general concept of a real wind energy system (WES) that can integrate reserves power, this study has presented a detailed model of WES, as shown in Fig. 2, to support the grid at primary and secondary levels.[33] The wind farm has two parts: an active power controller and a generator, which is immensely important in determining the wind farm response at the turbine level. Conversely, the active power controller assumes the task of establishing the required power setting ($P_{ref\_WT}$) for each wind turbine, considering the reference input at the wind farm scale and the immediate grid power. The control of power, through primary and secondary responses, is effectuated using input signals ($\Delta Pc$) derived from the governor and the AGC system. In situations involving the secondary response, power dispatch from the WES occurs according to inputs received from the AGC and the currently available input power. Further, the power controller at the wind farm level, while measuring the reference power $P_{ref\_WPP}$

**TABLE I.** Implementation of AGC strategies involving PV and wind energy sources. Abbreviations: OGSA: opposition-based gravitational search algorithm; CES: capacitive energy storage; FOPID: fractional order PID controller; MPC: model predictive control; and CES: capacitor energy storage.

| Ref. no. | Grid type | Regions | Generation sources | Device (additional) | Type of controller |
|---|---|---|---|---|---|
| 40 | Conventional | 4 | Hydro, thermal, and wind | ⋯ | PID with OGSA |
| 26 | Non-conventional | 1 | Wind-PV | ⋯ | AI-based FO-PID |
| 41 | Non-Conventional | 2 | Hydro, wind, and thermal | ⋯ | PI with GA |
| 42 | Conventional | 1 | Thermal and wind | ⋯ | MPC approach |
| 43 | Non-Conventional | 2 | Thermal and wind | ⋯ | MPC approach |
| 44 | Conventional | 3 | Thermal and wind | ⋯ | D-MPC approach |
| 47 | Conventional | 2 | Thermal and PV | ⋯ | PID with FA |
| 48 | Conventional | 3 | PV and thermal | ⋯ | I, PID with FWO |
| 49 | Conventional | 2 | Deiseal, wind, and hydro | AC and DC | PID with IPSO |
| 50 | Non-Conventional | 2 | Thermal, wind, and gas | TCPS, CES | I with ISE |
| 51 | Conventional | 2 | Wind and thermal | ⋯ | PID with HTGA |

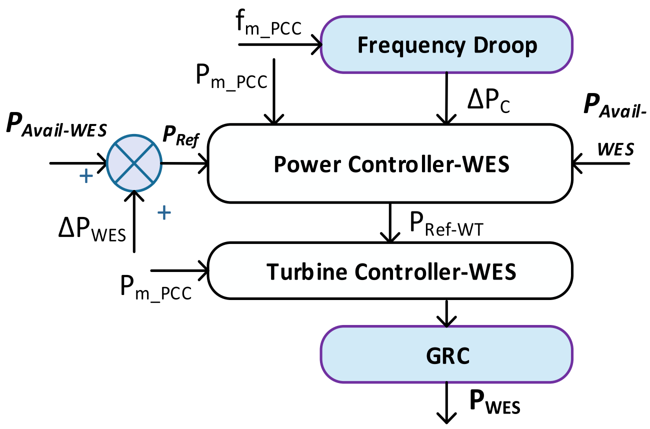



**FIG. 2.** Type 4 wind turbine system.

(Ref. 34), also incorporates the information related to the actual power, measured at the point of common coupling ($P_{meas\_PCC}$).

Wind turbines possess unique attributes that make them well suited for participation in these services.[14] Among the array of wind turbines, the commonly used three-blade configuration, which signifies the predominant selection, can be categorized into four categories based on their unique mechanisms.[11] This research focuses on type IV, characterized by variable-speed wind turbines equipped with converters. These advanced systems with variable-speed capabilities and integrated full-power converters exhibit remarkable potential for integration into AGC frameworks.

## B. Literature survey on wind energy based AGC systems

Substantial literature discussed the diverse control methodologies for acquiring regulatory power from WESs. Prevalent methods encompass AGC models based on the PI regulation, acknowledged for their simplicity and optimal efficacy. Researchers have examined a variety of parameters within these control approaches, including settling time, steady-state error, and overshoot. These works aim to enhance the robustness and efficiency of AGC models in power systems in large-scale, wind-powered, integrated systems. The upcoming investigations focus on innovative control approaches to improve wind farm performance within the AGC framework.

### 1. Intelligent schemes

In the current era of power methodologies, advanced strategies utilizing neural networks and fuzzy-based control schemes are developed to address the complex nonlinear challenges associated with integrating wind power into AGC services. A fuzzy logic controller (FLC) scheme is devised and implemented in this context to address the unpredictability of a highly intermittent wind energy system. This methodology involved analyzing the diverse system parameters and the experiential insights of system operators to derive fuzzy logic rules.[35] Conversely, neural network (NNC) employs a data-centric methodology, employing synthetic neural networks to comprehend the nonlinear correlations of AGC and wind energy systems. These neural networks are trained using historical data, allowing for predicting the required AGC parameters to maintain grid stability based on the current wind power production.[36,37] The authors in Ref. 36 developed a PI controller using fuzzy-based AGC to improve the efficiency in a two-area power network with a wind energy plant using doubly fed induction generators (DFIGs). The study showed that the fuzzy methodology has improved the effectiveness of handling frequency fluctuations with different load changes and wind speeds and performs better than a basic PI regulator. Furthermore, to enhance the efficiency of the fuzzy-based controller, researchers have integrated the PID regulators with fuzzy logic using the AI algorithms. The authors in Ref. 37 proposed an integrated control strategy that combines a PID regulator with fuzzy logic, employing the Jaya optimization algorithm. This approach was subsequently implemented within an AGC power network of three separate regions with wind turbines. The suggested controller was trained in various operational scenarios, which enhanced its effectiveness.

### 2. Control schemes involving optimization methods

Parameter optimization methods have been employed to enhance the performance of AGC systems. Identifying optimal values enhances precision in balancing power generation and demand. Advanced methodologies tackle constraints posed by fundamental optimization in certain wind turbine setups to support the AGC model. These approaches use advanced algorithms to fine-tune the operational wind turbines inside AGC systems, ensuring their operation at optimum efficiency and optimal efficacy. Among the methods employed are Cuckoo Search with Random Search Probability Optimization (CRSPO),[38] Ant Colony Optimization (ACO),[39] Opposition-based gravitational search algorithm (OGSA),[40] and Genetic Algorithm (GA).[41] Each technique provides various benefits tailored to the wind turbine configuration's requirements and AGC implementation. Using these optimization approaches has considerably improved the efficiency of wind turbines in AGC operations, allowing them to play an active part in maintaining system frequency and power balance. Using these algorithms and computational methodologies, wind turbine systems may be fully integrated into AGC operations, building a future with stronger and more efficient power generation. The authors in Ref. 39 introduced an innovative strategy artificial lion optimization (ALO) based AGC algorithm for enhancing the grid characteristics of the trajectory-tracking controller in wind turbine design. Compared to PI and PID controllers, ALO produced much better results, lowering peak overshooting and the time necessary for the system to achieve frequency stability.

### 3. Model predictive and control schemes integrating ESS and FACTs devices

Research studies, as mentioned in Refs. 42–44, support the effective integration of wind farms into AGC frameworks by implementing the model predictive control (MPC) techniques. Optimizing MPC is performed iteratively at every time interval, computing a new vector of control inputs for the system while considering the inherent constraints. The applications of MPC are expanded to encompass AGC scenarios in isolated[42] and interconnected multi-region power networks.[43] It effectively enhances the operational efficiency of systems integrating DFIG-based wind farms. Further, the strategy considers governor and turbine parameter fluctuations alongside power consumption pattern oscillations. Integrating MPC-AGC with wind power introduces a significant complexity inherent in control system engineering architecture. Furthermore, the implementation of MPC holds the potential to improve the operational efficiency and reliability of power grids, contributing to the establishment of an environmentally sustainable and secure energy framework.

To enhance the efficacy of the MPC approach within AGC systems employing wind farms, a decentralized MPC strategy named DMPC is used.[44] The DMPC methodology divides the system into subsystems, each controlled by a localized MPC controller. This distributed framework offers several advantages over traditional centralized or basic MPC techniques, including increased robustness against disturbances and more efficient utilization of system resources, ultimately enhancing the effectiveness of the AGC's functionality. The inherent distribution in DMPC facilitates immediate, precise regulation of every subsystem, thereby enhancing the comprehensive steadiness and dependability of the entire system. As a result, DMPC serves as a robust solution designed to improve the efficiency of AGC systems utilizing MPC principles, particularly in the context of wind farm integration. ESS and FACTS devices significantly promise to improve frequency management within multi-area power networks. FACTS mechanisms can enhance frequency control by regulating power flow along interconnection lines. FACTS and ESS devices are recognized as the leading instruments, enabling wind farms to contribute substantially to grid operational efficiency. Supporting this claim, Hui and Wen[45] integrated flywheel storage techniques into wind farm infrastructures.

This integration led to a decrease in settling time and more effective mitigation of frequency deviations, highlighting the inherent benefits of this innovation for strengthening frequency regulation within wind farm environments. Reference 46 exemplified the synchronized configuration of redox flow battery bank (RFB) and AGC to mitigate frequency deviations within multi-area power networks that incorporate wind farms. The study demonstrates a significant improvement in modulating and regulating frequency within power grids integrating wind energy. This improvement is achieved through collaborative fine-tuning of RFB and AGC components. The setup utilizes advanced optimization methods to minimize frequency deviations within power grids, ensuring consistent and reliable operation. Table I outlines the key aspects of various control schemes used in wind energy-based AGC models.

## IV. PROPOSED POWER GRID MODEL WITH OPTIMIZED AGC SYSTEM

The frequency variations within the electrical grid stem from a deviation between the generated electrical power and the required power demand. When the generated power ($P_G$) and the power demanded ($P_D$) match, the system's frequency remains consistently set at 50/60 Hz. However, upon a mismatch, the frequency initiates a deviation with frequency rates subject to the degree of power imbalance. It exhibits an inverse relationship with the system's inertia constant, as interpreted by the following swing equation:

$$\Delta f = \frac{f_{ref}}{2HS}(\mathbf{P}_m - \mathbf{P}_e). \tag{4}$$

The quantity $(\mathbf{P}_m - \mathbf{P}_e)$ represents the disparity between mechanical and electrical power, indicating the magnitude of the power imbalance within the system. S represents the power source rating, while H denotes the system inertia constant. Δf corresponds to the frequency variations. The AGC maintains the synchronism between the load and generation in a power grid, which measures the deviation in the system frequency and adjusts the generator's outputs taking part in AGC operation. Within the domain of AGC, the pivotal input given to the AGC controller for the regulation of network frequency and the provisions of interchange power at the selected threshold is denoted as an area control error ($\boldsymbol{P_{ACE}}$). The expression for $\boldsymbol{P_{ACE}}$ is as follows:

$$\boldsymbol{P_{ACE}} = \sum_{j \in \mathcal{A}_n} \boldsymbol{\beta \Delta f} + \left(\boldsymbol{P}_j^{Ref} - \boldsymbol{P}_j^{meas}\right). \tag{5}$$

The symbol $\beta$ signifies the constant factor of area bias, whereas Δf symbolizes the deviation in the system's frequency. $\beta$ is precisely characterized as the sum of D and 1/R. Upon an inconsistency between the electrical supply and demand, the velocity regulator promptly initiates the FCR mechanism to regulate the system frequency. Concurrently, the AGC mechanism will engage and intelligently detect any oscillations in the $\mathbf{P_{ACE}}$ parameter, prompting the AGC system to activate the frequency restoration reserve (FRR) mechanism for the precise calibration of $\mathbf{P_{ACE}}$. This ensures that primary reserves are conserved for future use. To achieve this objective, the AGC regulators must collaborate and coordinate their efforts, carefully adjusting the reference benchmark ($\Delta\mathbf{P_{ref-Gi}}$) for each of the generators participating in AGC operations. By adopting these control methodologies, the system promptly responds to fluctuations in power, ensuring a robust and uninterrupted electricity supply. Furthermore, a PI controller is integrated into the AGC structure to improve the $\mathbf{P_{ACE}}$ component (6), ultimately restoring the system to its state of operational equilibrium. The function of the PI controller is executed by modifying generator outputs, attained through computation of the error signal that differentiates the set reference level from the real output. This error signal is subsequently integrated over a period,

$$\Delta P_{Sec} = K.\Delta P_{ACE} + KT\int \Delta P_{ACE}dt. \tag{6}$$

Accurately determining the values of parameters K and T is essential for stabilizing the system frequency at its level and maintaining the exchanged power within pre-determined thresholds. The selection process for these parameters follows a well-defined protocol inherent to an AGC model. The coefficient (K) is customarily modifiable from 0 to 0.5, while the time coefficient (T) is amenable to adjustments in the 50–200 s range. In the AGC process, the time constant assumes a vital function. The AGC scheme is developed to provide reserve energy proficiently by integrating a WES and a flexible load system. Figure 3 explains a comprehensive configuration of the power network, integrating the output capacities of diverse power-generating units, such as gas, thermal, and WES. The continuous line represents electrical current transmission, whereas the dashed line denotes data exchange. Moreover, to amplify the inertial response of the grid, the system is linked to the external network, resulting in a feedback of 6261 MW/Hz for 15 s. For simulation analysis, the capacities and regulatory reserves of various generation units and adaptable loads are mentioned in Table II.

### A. Wind energy system

Figure 4 shows a dynamic figure of the wind energy system (WES), demonstrating its capacity to deliver additional services.[12]

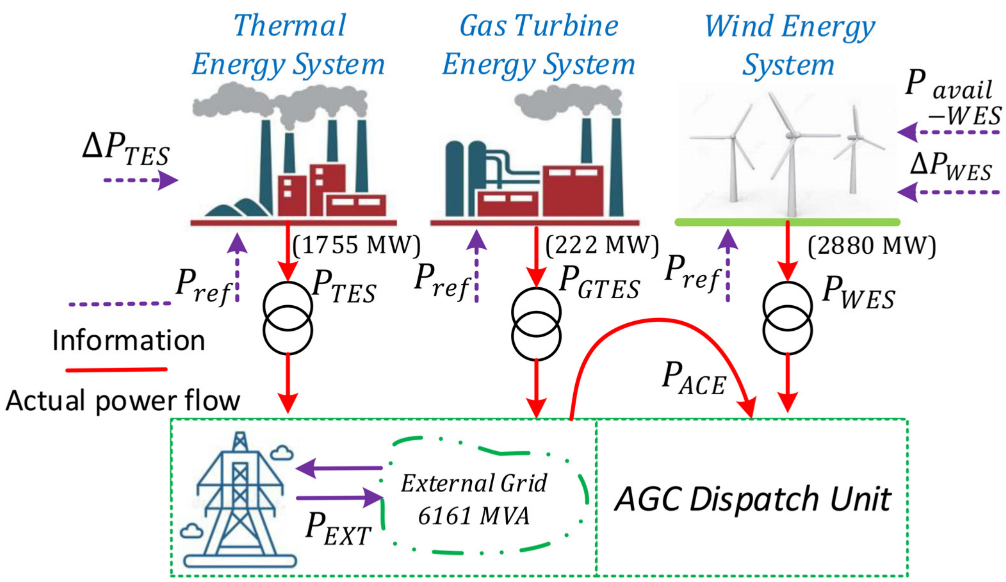



FIG. 3. Proposed power network with AGC model.

The model plays an important role in measuring the function of wind turbines in guaranteeing stability and supplying active power within the power system. WES evaluates wind energy properties on a whole system level, which is more important than anticipating the impact of individual wind farms. This is owing to the emphasis assigned to the overall efficiency of various wind generating installations. With this model, the research may acquire a more thorough knowledge of the operational dynamics of wind power plants, which is crucial for professional analysis and management of power systems. This model is developed and optimized for controlling active power and carrying out extensive dynamic simulation investigations. By incorporating these modifications, the inquiry intends to improve the model's adaptability for assessing and attaining an in-depth understanding of the operational dynamics of wind energy-based power plants in grid management and supervision. Figure 4 depicts a detailed breakdown of three unique components: the active power control unit for the wind energy system (WESAPC), the active power control unit for the wind turbine (WTAPC), and the generator reference current segment.

The wind energy-derived power plant's indicative power ($P_{ref\_WT}$) originates from the WESAPC segment within the arrangement, responsible for computing the point of reference power at the plant scale $P_{ref\_WES}$. Within this scope, the determination of $P_{ref\_WPP}$ is formulated based on the input from the frequency-deviation signal ($\Delta P_c$), the signal signifying the power reference input $P_{ref}$ and the quantified power value ($P_{meas\_PCC}$). Further, the variance between $P_{ref\_WES}$ and $P_{meas\_PCC}$ is derived by the PI regulator. At the turbine level, the resulting output signal is considered as the current $I_{Pcmd}$, an outcome originating from the PI controller as a difference between ($P_{ref\_WT}$) and $P_{meas\_PCC}$. This study assessed type IV wind turbine technology, characterized by distinct converters operating independently. This design offers greater operational versatility compared to traditional turbines. The machine-side converter assumes control over the rotational velocity of the generator, while the grid-side converters autonomously manage the regulation of active power transmission into the grid.

A stationary generator based on the current source model comprehensively evaluates wind turbine response across various scenarios. This approach offers significant advantages over alternative methods and constitutes a fundamental aspect of research methodology. Moreover, wind power can rapidly adjust to fluctuations in system frequency within 2–5 s, adhering to the constraint imposed on the modification rate in the reference parameter. The developed wind energy system (WES) model shows effectiveness in providing both positive and negative regulating power during power balance adjustments. However, excess reserves within the WES may increase operational costs, as conventional power generators must provide reserves for expected deviations. Optimizing the use of wind energy installations is financially beneficial and aligns with the flexibility of power output adjustments.

TABLE II. Generating units parameters (MW).

| Power system units | TPS | GTES | WES |
|---|---|---|---|
| Capacities | 1755 | 222 | 2880 |
| Reserves on AGC | 0 | 0 | −500 |

## B. Thermal power system

The paper examines the efficacy of a TPS model in actively managing power dynamics. Figure 5 encompasses both primary and secondary control mechanisms.[12] The composite power system model illustrates that thermal energy contributes to the initial frequency response through the governor. The output of the turbine on the mechanical power ($P_{mech}$) stems from the governor and the steam pressure ($P_t$) originates in the boiler component. The reference load

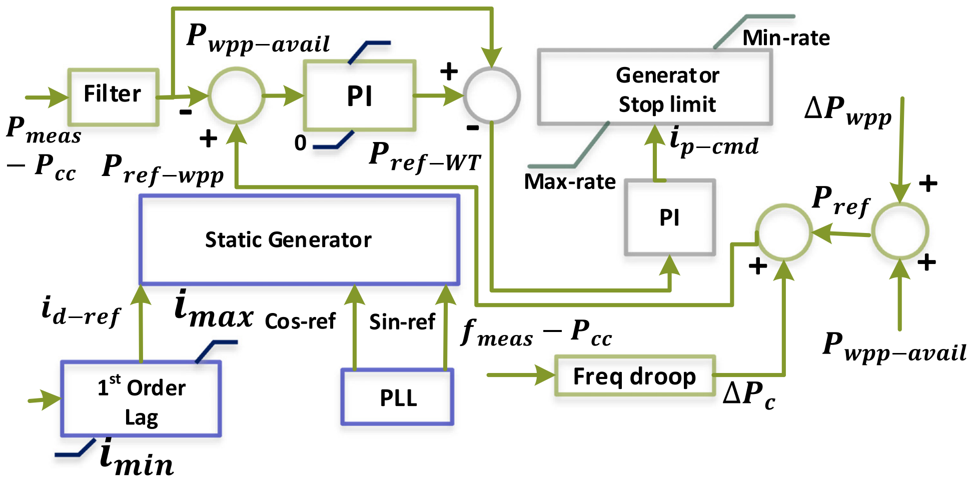



FIG. 4. Wind energy system design.

signal helps balance changes in the load ($L_R$), providing important information to the boiler segment to compute a new steam pressure value ($P_t$).

The adjusted steam pressure is determined while considering the turbine's operational limitations and the delays associated with the steam energy stored in the boiler. Furthermore, the model accounts for the effects of GRC and STC, which limit the rate of change to a maximum of 30 MW/min. The speed governor initiates the primary response, considering the input of speed deviation and the predetermined droop settings of the turbine. To mitigate potential disruptions caused by minor mechanical disturbances, the model includes inactive regions, known as dead zones, for the governor valve.

### C. Gas turbine energy system

The study has designed an energy system based on a gas turbine design to provide the initial frequency response through the main governing mechanisms.[12] This model includes a dead zone and a low-pass filter to prevent any turbine damage from minor oscillations. Harnessing the frequency droop characteristic of the turbine and the potential of the frequency signal to fluctuate, the power plant generates a power requisition signal ($\Delta P_c$), subsequently utilized as an input to the power plant system. The power plant configuration comprises three essential elements: a power limitation module, a power distribution module, and the gas turbine, as depicted in Fig. 6.

The power limitation module imposed constraints on the turbine's response using thresholds, $P_{max}$ and $P_{min}$, within the reference power signal. These thresholds are defined based on the inherent limitations of combustion technology. The power limitation module generates a predefined load signal as input for the power distribution segment. This constraint component considers a number of combustion chambers that operate. The mechanical output of the turbine ($P_{mech}$) is confined within the boundaries of maximum and minimum power levels, reliant on various signals, including CSEV, CVGV, CLC, CEV, and CFM. The gas turbine takes approximately 25–30 s to respond to any change in the frequency pattern, considering the interconnected limitations and constraints associated with the alteration rate.

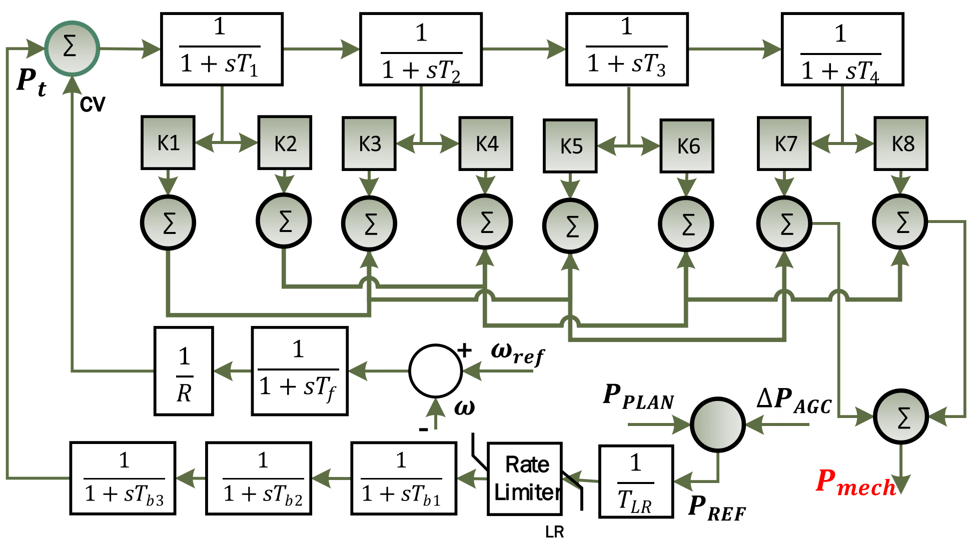



FIG. 5. Thermal energy system.

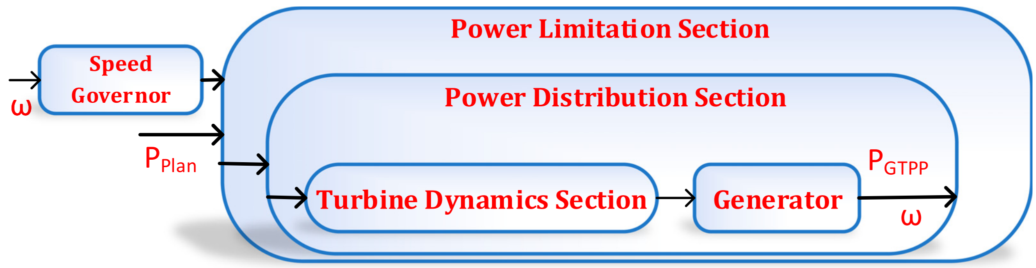



**FIG. 6.** Gas turbine energy system.

## D. Proposed AGC dispatch scheme

Traditionally, conventional power plants assumed the role of supplying the required power for system equilibrium. However, the modern power grid extensively integrates renewable energy sources, particularly wind power generators, which display unpredictability and consistently contribute to forecast inaccuracies. Consequently, this required an increased allocation of balancing power to ensure the reliable operation of the power grid. A substantial proportion of secondary reserves, crucial for system equilibrium, is currently supplied by conventional power plants. However, this approach concurrently enhances the operational expenses and environmental concerns. In this context, it becomes imperative to explore novel control and equilibrium strategies, such as harnessing regulation reserves sourced from WESs, while concurrently examining wind power plants' capacities in accordance with TPSs.

In this case study, an integrated control approach is formulated to manage the dispatch operation of WESs and TPSs. This strategy considers factors such as the upper limits of generating unit capacity, the availability of reserves, and generation costs. The response of the WES to changes in both upward and downward power regulation is enabled by the activation of the delta production constraint mechanism. In accordance with the conditions specified in directive TF 3.2.5, a grid-connected wind turbine operating at a voltage surpassing 100 kV and featuring the delta production constraint mechanism manages the delivery of regulation power by limiting the power generated from the current operation within WESs. As a result, a pre-determined amount of power is allocated to address regulatory issues. A methodology is used for integrating WES into the AGC system, focusing on mitigating negative power imbalances. As previously discussed, WESs can contribute to positive regulation power. However, this effort would lead to increased operational costs, as the reserved power obtained from WESs would require support from TPSs or imports from other power systems if not used in AGC operations. Therefore, it becomes more financially prudent to maximize power production from WESs at their highest potential, owing to their lower incremental cost, and only curtail their power generation when an excess of energy generation prevails.

This case study introduces a methodology aimed at integrating wind power resources into the operational framework of AGC. This integration balances power imbalances within the grid, especially when WES are heavily involved in electricity generation, and TPSs are operating near their minimum thresholds, preventing further downregulation in cases of power oversupply. The dispatch strategy's procedural depiction is illustrated in Fig. 7, based on minimizing costs function. Reserves obtained from WES are only mobilized in cases of surplus power generation, specifically when $\Delta P_s < 0$. Conversely, reserves

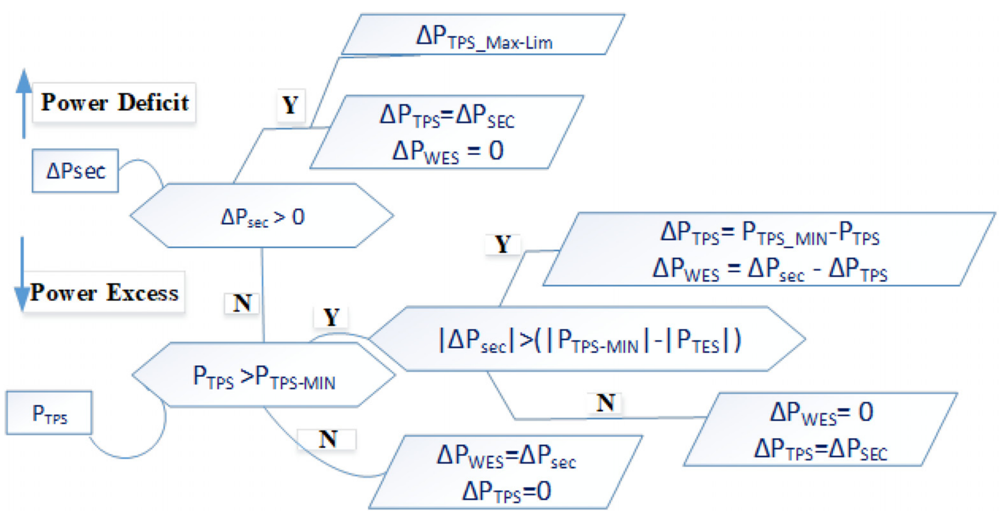



**FIG. 7.** Proposed dispatch strategy for the integration of wind power resources into the operational AGC framework.

stemming from TPS (±100 MW) are engaged in periods of excess and deficiency of power generation. In the proposed dispatch strategy, the reduction in power output from the wind power plant only works under two conditions: first, when the TPS is operating at its lower threshold ($P_{TPS,\,min}$), which is typically fixed at 25% of its total capacity, and second, when the secondary dispatch from AGC reaches its nadir ($\Delta P_{TPS,\,min}$), corresponding to $-100$ MW. In conditions where TPS's contribution to effective power regulation is constrained, the WES dispatch regulates $P_{ACE}$ by curbing energy output as per the requisites of the system.

However, in instances requiring positive regulation, $\Delta P_s > 0$, the AGC triggers an instruction for the WES. However, the WES is excluded from delivering a response due to its existing operation at maximum capacity. In this scenario, the complete regulatory response is facilitated through the TPS system, which activates its secondary reserves. This control method involves fully utilizing the WES at its maximum capacity, thus providing conventional power plants (CPP) the flexibility to operate within their lower operational limits. This collaborative approach results in lower overall operational costs and reduces $CO_2$ emissions. The process of positive dispatch is explained through Eqs. (7) and (8), while the process of down-regulation is detailed in Eqs. (9)–(14). This set of equations outlines the parameters that constrain the determination of real-time dispatch decisions.

Positive dispatch is

$$\begin{cases} \Delta P \geq 0 \ (\text{Up} - \text{Regulation}) & (7) \\ \Delta P_{\text{sec}} = \Delta P_{TPS}, & (8) \end{cases}$$

subject to

$$\Delta P_{TPS} < \Delta P_{TPS-max\,limit}. \quad (9)$$

Negative dispatch is

$$\begin{cases} \Delta P < 0 \ (\text{Down} - \text{Regulation}), & (10) \\ \Delta P_{sec} = \Delta P_{TPS} + \Delta P_{WES}, & (11) \end{cases}$$

subject to

$$\begin{cases} \Delta P_{TPS} > \Delta P_{TPS-min\,limit}, & (12) \\ P_{TPS} > P_{TPS-min}, & (13) \\ \Delta P_{WES} > \Delta P_{WES-min\,limit}. & (14) \end{cases}$$

## E. Results and discussion

In conjunction with CPP, this integration of wind energy enhances the security of power balancing operations by improving the secondary reserves. Further, this approach allows CPPs to operate close to their lower limits, resulting in a reduction of the overall operational costs. The proposed dispatch approach aims to minimize costs. The utilization of reserves sourced from WES is enacted in scenarios of surplus generation, denoted as $\Delta P_s < 0$. Meanwhile, reserves from TPS (±100 MW) are called upon in excess and deficiency in power generation. Further, the reduction in power output from wind energy systems occurs solely when TPS is operating at its minimum capacity ($P_{TPS,\,min}$), typically set around 20% of its total capacity or when the secondary dispatch from the AGC reaches its lower threshold ($\Delta P_{TPS,\,min}$), which is $-100$ MW. The utilization of reserves sourced from WES is limited to moments of surplus generation ($\Delta P_s < 0$), while TPS reserves (±100 MW) are engaged in excessive and insufficient power generation. Moreover, the reduction in power generation from WES occurs exclusively when TPS is functioning at its minimum capacity $P_{TPS,\,min}$, commonly set at around 20% of its full capability or when the secondary dispatch from the AGC attains its lower threshold ($\Delta P_{TPS,\,min}$), equivalent to $-100$ MW. Upon the TPS reaching its capacity to contribute to effective power control, the WES dispatch manages the remaining $P_{ACE}$. Nevertheless, in situations requiring positive regulation $\Delta P_s > 0$, AGC generates an instruction for the WES; however, a response is unattainable due to the WES already operating at its full capability. As the TPS reaches its limit, the wind energy system dispatch assumes responsibility for regulating the remaining $P_{ACE}$, adhering to the system's requirements by restricting energy output. However, when up-regulation becomes required, i.e., $\Delta P_s > 0$ AGC issues a command to the WES, but the response is unavailable since the WES is already operating at maximum capacity. The TPS assumes complete regulation control in such a scenario, activating its supplementary reserves. This approach to regulation considers the WES to its full potential while enabling the TPSs to function at their minimal thresholds, thereby efficiently reducing the total operational expenditure and carbon dioxide emissions.

Figure 8 illustrates the power imbalances initially requiring attenuation, utilizing control reserves from the WESs and TPSs. To reinstate the frequency to its designated level, the AGC system triggers FRR. The AGC's reaction is based upon the computed ACE signal, *fun*ctioning as *an* input to the PI controller, which establishes the necessary secondary adjustment $\Delta P_{Sec}$ for the generation units. Afterward, the $\Delta P_{Sec}$ indication is transmitted to the power allocation module,

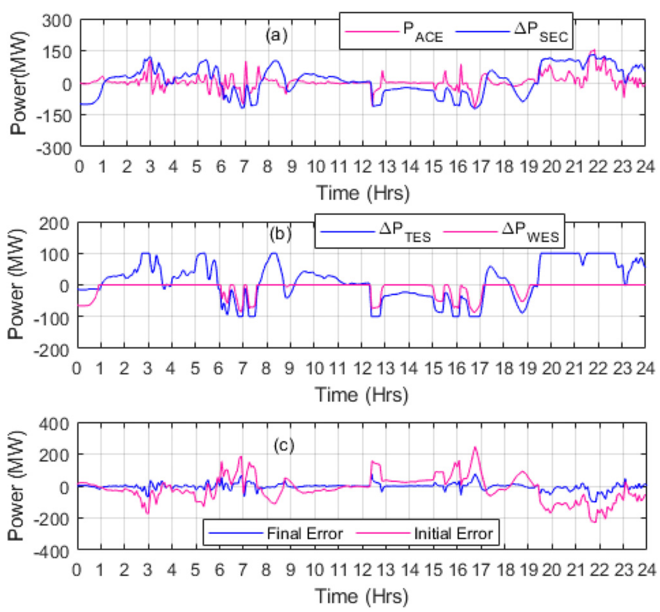



**FIG. 8.** (a) ACE and essential secondary adjustment, (b) controlled AGC dispatch power from TPS and WES, and (c) initial vs final power error following AGC response.

deciding changes in reference values for operative generation units ($\Delta P_{WES}$ and $\Delta P_{TPS}$). In Fig. 8(a), the illustration displays $P_{ACE}$ and $\Delta P_{Sec}$ (overall secondary dispatch), with $\Delta P_{Sec}$ trailing behind the $P_{ACE}$ signal due to inherent delays in the AGC mechanism and the response times of power installations. Figure 8(b) exhibits the individual response ($\Delta P_{WGS}$ and $\Delta P_{TPS}$) of the TPS and WES units in response to the ACE signal. The WES governs its output in accordance with the AGC directive during the TPS allocation. $\Delta P_{TES}$ decreases to the minimum threshold (−100 MW) or when it functions at its lowest generation limit (20% of the operational capacity). Utilizing the FRR ($\Delta P_{WES}$ and $\Delta P_{TPS}$) efficiently mitigates the overall power errors revealed through $P_{ACE}$. Figure 8(c) shows that incorporating WES has notably mitigated power imbalances, particularly during surplus power generation. Hence, the dynamic integration of wind power into the AGC dispatch strategy is a viable option for active power equilibrium control within power system networks based on substantial wind power integration. The stable frequency achieved following the AGC reaction is displayed in Fig. 9.

## V. CONCLUSIONS AND FUTURE DIRECTIONS

The massive penetration of clean energy sources in conventional power networks requires extra electrical capacity to counteract the forecasting errors due to the large-scale wind and solar energy systems. Wind and solar energy sources play vital roles in AGC services to maintain real-time equilibrium between power demand and generation while minimizing the reliance on excessive power reserves. This is especially noticeable when these renewable energy assets are integrated into different areas in a diverse range of technology-driven power generation networks. This research explored wind farms and solar PV, emphasizing their roles in LFC—a pivotal aspect of AGC. The study thoroughly evaluated contemporary and historical AGC practices when regulating power derived from wind farms and PV systems. The research examined and compared various traditional and contemporary AGC control mechanisms. To elaborate this new concept further, the study developed an AGC system incorporating a dynamic real-time dispatch technique to harness the reserve power generated by wind farms and thermal power systems. The proposed control strategy was implemented by developing a modern power using Dig Silent Power Factory software, encompassing both renewable and traditional generating units. The findings illustrated that using wind power in AGC services can efficiently alleviate power imbalances while retaining the system's operational security. Moreover, the findings of this study have paved the way for incorporating large-scale solar energy systems into AGC services, which is an effective step forward in enhancing overall grid resilience and sustainability.

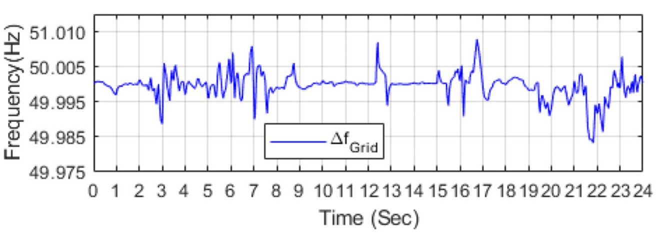



**FIG. 9.** Grid frequency following secondary response from TPSs and WES.

In the future, innovative approaches to managing AGC systems may be developed, leveraging state-of-the-art AI technologies to forecast various grid parameters precisely. This could, in effect, reduce discrepancies and enhance the system's overall efficiency.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Kaleem Ullah:** Conceptualization (equal); Formal analysis (equal); Methodology (equal); Software (equal); Supervision (lead); Visualization (equal); Writing – original draft (equal). **Majid Ali Tunio:** Conceptualization (equal); Formal analysis (equal); Project administration (equal); Validation (equal); Writing – original draft (equal). **Zahid Ullah:** Conceptualization (equal); Investigation (equal); Methodology (equal); Project administration (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Muhammad Talha Ejaz:** Data curation (equal); Investigation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing – original draft (equal). **Muhammad Junaid Anwar:** Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal). **Muhammad Ahsan:** Data curation (equal); Formal analysis (equal); Methodology (equal); Visualization (equal); Writing – review & editing (equal). **Ritesh Tandon:** Data curation (equal); Validation (equal); Visualization (equal); Writing – review & editing (equal).

## DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

## NOMENCLATURE

| | |
|---|---|
| CESs | Capacitive energy storage system |
| CEV | Environmental burning capacity |
| CFM | Baseload function |
| CSEV | Sequential environmental burner capacity |
| CVGV | Variable inlet guide vane position compressor capacity |
| FRR | Frequency regulation reserves |
| GTDB | Gas turbine dynamics block |
| GTES | Gas turbine energy system |
| PDB | Power distribution block |
| PLB | Power limitation block |
| PJM | Regional transmission company |
| SEV | Sequential environmental combustion |
| SMA | Smart management approach |
| SEV | Sequential environmental combustion |
| TSO | Transmission system operator |
| TPS | Thermal power system |

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