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Research Article

Line Congestion Management in Modern Power Systems: A Case Study of Pakistan

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The surging electricity demand in Pakistan has led to frequent blackouts, prompting government initiatives to expand power plant capacities and improve the national grid. The government prioritizes integrating large-scale renewable energy sources, such as wind and solar power, to reduce dependence on conventional power plants. However, the intermittency of renewables leads to forecasting errors, requiring extra power reserves from conventional units, thereby escalating operational costs and CO_2 emissions. The country currently utilizes a manual mechanism for power balancing operations, overlooking critical grid constraints of the transmission line loadings. In such conditions, injecting large-scale power from renewables can lead to significant fluctuations in line power flows, risking transmission line loadings and compromising the system's secure operation. Hence, this paper has developed an automatic generation control (AGC) model for the highly wind-integrated power system to alleviate line congestions in the network and enhance the economic operation of the system. The study utilizes the Pakistan power system as a case study to simulate the proposed model. The developed real-time power dispatch strategy for the AGC system considers the constraints of the transmission line to avoid congestion. It integrates wind energy as operating reserves to enhance the economic operation of the system. When managing line congestion, it identifies overloaded bus lines and adjusts power regulation accordingly while compensating for shortfalls by augmenting transmitted power from regional grid stations. However, it maintains a constant dispatch ratio without line overloads, aligned with generation capacities. Additionally, the strategy integrates reserve power from the wind power plant and traditional generating units to further improve economic operations. Simulations have been conducted using PowerFactory software, employing the eight-bus and five-machine models to replicate the characteristics of the Pakistan power system. The results demonstrate the effectiveness of the proposed AGC design in mitigating transmission line congestion of power systems that are heavily integrated with wind energy sources while simultaneously ensuring the economic operation of generating units.

1. Introduction

Following the deregulation, the Pakistani power system shifted from a vertically integrated model overseen by WAPDA to a decentralized structure. WAPDA now focuses on water resources and hydroelectric power, while other entities like GENCOs, NTDC, and DISCOs handle generation, transmission, and distribution. PEPCO oversees four GENCOs, ten DISCOs, and NTDC as the grid operator [1, 2]. The power transmission system in Pakistan spans various voltage levels, including 500 kV, 220 kV, and 132 kV lines. NTDC Pakistan is responsible for maintaining and operating the 500 kV and 220 kV grid stations and transmission lines [3]. The transmission system is configured as a ring connection, interconnecting generating units from diverse sources. As of March 2021, NTDC oversees nineteen

500 kV grid stations and forty-four 220 kV grid stations. NTDC balances electricity demand and supply as a system operator, especially with growing competition in the generation sector [4]. It manages the dispatch control mechanism and supervises network interactions for power balance operations.

The country relies on manual power dispatch to balance the supply and demand chain by regulating the network frequency within acceptable limits. This process is performed minute-to-minute, requiring the activation and injection of additional reserves within the acceptable time range of 5 to 10 minutes. However, contrary to standard practices, the manual process in the country often surpasses this time limit, resulting in delayed responses to real-time demand fluctuations. This delay risks system stability and causes chain reactions of tripping incidents. Furthermore, in the manual process, the system operator does not consider the loading levels of the transmission lines and lacks a proper way of prioritizing the activation of generation units based on their economic status. This has resulted in many unplanned outages in the network. For instance, in 2006, NTDC recorded 140 scheduled outages in 500 kV lines and 657 in 220 kV lines. Additionally, there were 29 forced outages in 500 kV lines and 351 in 220 kV lines [5, 6]. The frequency of these outages increased in 2007, further revealing the inefficiency of the network dispatch system. The country relies solely on conventional power plant units for operating reserves, amplifying operational costs and CO_2 emissions. However, the country possesses substantial wind and solar energy potential [7–10], particularly with wind energy being recognized as a sustainable source with a capacity of up to 350,000 MW [11]. However, wind power plants are susceptible to forecasting errors, necessitating supplemental reserves from conventional power plant units. Therefore, to counter the aforementioned challenges in the network, an optimal and dynamic automatic generation control (AGC) system is required to automate the power dispatch system by considering network constraints and efficiently integrating wind power sources into the operational reserves alongside conventional power units. Such measures would fortify the security and reliability of the prevailing power network infrastructure.

1.1. Related Work. This study has conducted a detailed literature survey on the automatic generation control (AGC) system addressing the line congestion management issues and integrating the wind power plant system for the operating reserves [12, 13]. Much of the research literature has covered two main approaches to address line congestion in the AGC system: the cost-free mean and the cost-free approaches [14, 15]. The cost-free method works on rerouting power flows in congested lines or utilizing FACTS devices, as their usage incurs minimal marginal costs rather than substantial capital costs. The latter method, which comes with associated costs, involves implementing actions such as redistributing the production outputs of specific generators. This can be achieved by decreasing the output of particular generators while simultaneously increasing the output of others, resulting in changes to their incremental costs. The focus of this study is centred around this particular approach. In this approach, the power dispatch of the power plant is adjusted to avoid congestion in the transmission lines. The authors in [16] proposed an enhanced approach to effectively control power flow in power systems driven by renewable energy sources to prevent transmission line overloading. A comprehensive dispatching mechanism for the AGC system has been designed to address this issue by managing the power flow in highly loaded lines by utilizing the untapped capacity of lightly loaded lines, which serve as a buffer to accommodate fluctuations in power output. However, the study has limitations during the effective operation of AGC, when all lines operate at their intended levels, because the model heavily relies on the available capacity of lightly loaded lines.

The study [17] proposed a dynamic control mechanism for the AGC system to reorganize the power generation of the units after encountering N-1 contingencies in the network. The readjustment of the power is carried out at the receiving bus of the line, which passes the loading threshold and is contingent upon the excess power magnitude in each iteration of the load flow solution. This method was proven effective with a limitation of notable time consumption by utilizing the trial-and-error method. The authors of [18] proposed an AGC controller based on synchrophasor measurements to redispatch power generation units to manage line congestion in the network. The study utilized the predictive control strategy based on the disturbance compensation method, which ensures real-time power flow regulation while considering various grid constraints. The power grid partitioning method is developed [19] to reduce line congestion in the network, utilizing the techniques of power tracing and sensitivity analysis. The proposed technique assigns a congestion index to each candidate zone to measure the percentage of zones that can effectively participate in load alleviation in the network. This technique assists the system operator in specifying the specific zone in the network that is mainly responsible for creating line congestion. The study [20] proposed an MPC-based AGC strategy to address the line congestion in the transmission network by categorizing consumer demand into controllable and noncontrollable loads. Mixed Integer Quadratic Program optimization problems have been used to formulate these methodologies.

Nonlinear programming techniques have also been implemented to address the line-loading phenomena in power networks incorporating large-scale renewable energy sources. These studies aim to achieve well-coordinated control actions to tackle issues related to the power network having bulk RESs. The authors in [21] conducted a detailed study on developing a fuzzy adaptive bacterial foraging- (FABF-) based AGC system to reschedule power generation to alleviate line overloads and enhance the economic operation of the network. The proposed model was compared with the simple particle swam optimization and bacterial foraging-based AGC techniques to demonstrate the effectiveness in mitigating line congestion in highly RES-based power grids. In [22], the researchers considered an approach based on machine learning while incorporating classical constraints to tackle the issue of line overload alleviation along with economic dispatch in RESs-based networks. The authors in [23] have developed an efficient power dispatch control system by leveraging an economic model that utilizes the direct acyclic graph (DAG) method. This innovative approach allows for optimized allocation of power generation resources, resulting in improved operational efficiency and cost-effectiveness in large-scale integrated power networks. The authors in [24] introduced a model for the power dispatch specifically developed to mitigate line overloads utilizing a mixed linear programming technique, which aims to minimize switch openings to reduce the frequency of overloads effectively. However, the study described in [25] proposes an innovative fuzzy logic model to mitigate transmission line overloads, striving to replicate the actions of network operators. It is worth noting that this approach does not consider generation cost.

1.2. Research Gap and Paper Contribution. The aforementioned works address potential solutions for line congestion problems in large-scale power system networks. However, these studies lack real-time models of the AGC system, which consider network operational constraints, including the loading limits of the transmission lines and the economic priority of the generating units during the power system balancing dispatch process. Furthermore, integrating large-scale wind energy into the AGC system to support ancillary services is also a potential challenge that needs to be addressed. Subsequently, this represents a crucial gap in the existing literature, as it fails to address the challenges of line congestion in highly wind power-integrated systems. Based on the above analysis, this research modelled a dynamic and real-time AGC system for power system networks integrating large-scale wind power energy systems. The proposed control design integrates a dynamic AGC dispatch strategy, considering constraints imposed by transmission lines and available reserve limits before power dispatch events during power balancing operations. In managing line congestion, the proposed dispatch strategy specifies the overloaded bus line and calculates the strength of the significantly overloaded power. Power in the connected bus of the overloaded line is then restricted by regulating the power of associated generating units while simultaneously addressing shortfalls by augmenting transmitted power from the regional grid station connected to the overloaded node. However, in the absence of line overloads, the dispatch ratio remains constant, aligned with the ratio of generation capacities. Hence, the proposed dispatch approach effectively addresses line overload issues that may arise after N-1 contingencies while ensuring the economical operation of power grids that incorporate large-scale integration of wind power systems. To ascertain the efficacy of the proposed approach, simulations are conducted using the DIgSILENT PowerFactory software, utilizing a 5-machine 8-bus network model of the power system of Pakistan. Some of the pertinent contributions of this work are as follows:

(i) An 8-bus 5-machine model of Pakistan's power system has been developed, encompassing a 500 kV transmission system and a model of a thermal generation system (TGS), wind generation system (WGS), and gas turbine generation system (GTGS).

(ii) An AGC system is developed for Pakistan's power system, and a dispatch strategy is designed and incorporated for line congestion management and reserve utilization of power from the WGS.

(iii) Real-time input time series data for the generating units and interconnected loads are employed to validate the efficacy of the proposed control methodology in the context of the AGC model for the power system.

1.3. Paper Outline. This paper is presented in the following sequence. Initially, in Section 2.1, the comprehensive AGC model of the system is developed, covering the operational aspects of the AGC and associated controller parameters. Moreover, this subsection details the integration methodology of the generating units and the 500 kV transmission lines within the AGC system. Subsequently, Section 2.2 elaborates on the power dispatch strategy designed for the AGC unit model. Section 2.3 addresses the modelling strategies for the power system generating units, including the wind, gas turbine, and thermal generation systems. The study has utilized the DIgSILENT PowerFactory software to model and validate the generating units. Section 3 focuses on validating the proposed AGC model using real-time data, particularly addressing power imbalances arising from wind power forecasting issues and their mitigation through utilizing operating reserves from wind and thermal generation systems while considering transmission line operational constraints. Furthermore, a comparative analysis of transmission line loading due to AGC response in power balancing operations is presented. The study results have revealed that integrating the proposed AGC model effectively addresses congestion management issues in the highly overloaded network while integrating reserve power from the wind and thermal power plants. This increases network reliability and reduces dependency on conventional power plant units. Finally, Section 4 concisely summarises research findings and insightful recommendations.

2. Power System Modelling

This section presents an in-depth analysis of the complex modelling aspects of the proposed automatic generation control (AGC) unit within the power system. Furthermore, it encompasses detailed information on the dispatch strategy employed within the AGC model and the explicit modelling of power generation units.

2.1. AGC Model Operation. The resilient and reliable functioning of the power grid hinges on the pivotal role played by AGC, which oversees the system frequency and promptly triggers corrective actions when required. Within the domain of AGC control, two crucial variables govern the operational dynamics: frequency deviations and power exchanges. These variables converge to formulate a unified equation known as the area control error (ACE), a critical component in implementing AGC control. The ACE equation in the i^{th} area is expressed as follows:

$$P_{\text{ACE},i} = \sum_{j\epsilon\mathcal{A}_n} \beta_i \Delta f + \Delta P_{ij}. \tag{1}$$

In (1), $P_{\text{ACE},i}$ denotes the power imbalance within the i^{th} area of the system after the load alteration. Δf represents frequency deviations, while β_i signifies the frequency bias constant specific to the i^{th} area. β_i can be derived from the equation $\beta_i = D_i + 1/R_i$, wherein D_i characterizes the damping of the network and R_i denotes the droop characteristics. In this specific study, R_i is consistently fixed at a predetermined value of 3.45%. The symbol ΔP_{ij} represents the collective variation in interchange power, signifying the disparity between the real and scheduled interchange power, commonly referred to as tie-line error. As a result of load changes within the network, the system frequency undergoes rapid fluctuations, prompting the activation of primary reserves through governors of generator units. Successively, the AGC calculates the necessary ACE, referred to as $P_{\text{ACE},i}$, and deploys the necessary reserves to settle down the system frequency and relieve the reserves at the primary control level. Such a procedure effectively restores the frequency to its nominal level, ensuring the operation of a secure and reliable power system. The operational timeframe of AGC typically ranges from 1 to 10 minutes.

Traditionally, the AGC system has been concentrated on regulating the P_{ACE} and tie-line interchanges, exclusively managing power flow within these specific parameters. However, this narrow focus neglects broader power flow regulation on other network lines, posing significant risks such as potential line overload during power balancing operations, which could lead to disruptions, equipment damage, and system failures in the power system. The consequent operational inefficiencies can impact economic power dispatch and overall system performance. A more comprehensive approach is required to address these implications, extending control to all network lines for enhanced resilience, stability, and efficiency under various operating conditions. Considering the substantial impact of AGC operations on active power flow, including injection by diverse components in the power grid, integrating line limits into the AGC dispatch process becomes crucial to address line congestion issues during power balancing operations effectively. Furthermore, extending reserve integration to wind power energy reduces grid dependency on traditional generating units. This investigation focuses on integrating transmission line system capacities into the AGC dispatch procedure, considering loading limits before power distribution among generating units. Consequently, fluctuations in power across transmission lines are managed through the recalibration of generating unit participation factors. The research also extends to integrating reserves from wind generation plants alongside thermal generation plants, thereby enhancing the economic security of system operations.

Figure 1 provides a visual representation of the network architecture of the implemented AGC system. The system utilizes an eight-bus, 5-machine model that accurately represents the country's power grid. The model incorporates a robust 500 kV transmission system and integrates multiple energy systems, including TGSs, GTGSs, and WGSs. These diverse energy generation systems are interconnected through a network of transmission lines, facilitating efficient power flow and control. Additionally, the network is linked to the external grid, which can offer an inertial response within 16 seconds. It is noteworthy to mention that the inertia unit adopted in this investigation is denoted in seconds. This decision aligns with the per-unit system, wherein inertia signifies the amount of energy per power unit, thus governing the rate at which power fluctuations occur within the grids. Additionally, the system response at the primary level from the external grid is fixed at 6060 MW/Hz, which signifies the grid's capacity to respond to variations in system frequency. For a comprehensive understanding of the interconnected buses and their respective transmission lines, refer to Table 1.

With the primary aim of mitigating transmission line overloads, this research has made certain simplifications to streamline the intricate model of the transmission line system. Certain parameters, such as line lengths and voltages, are excluded, as their inclusion is not deemed essential for the specific objective of this study. Moreover, the AGC implementation integrates a PI controller to minimize the area control error P_{ACE}, as defined in equation (2), thereby optimizing the regulation of the interconnected power system.

$$\Delta P_{\text{Sec}} = K.\, \Delta P_{\text{ACE}} + KT \int \Delta P_{\text{ACE}} \mathrm{d}t\, K. \tag{2}$$

Determining the K and T parameters is crucial in restoring the system frequency and regulating the power shared across the interchange line. These parameter values are determined per established criteria governing a secondary control system, as elucidated in reference [26]. The rate at which reserves are activated from the generating units is quantified by the controller's tracking speed, commonly known as the time constant. The magnitude of reserve power is referred to as ΔP_{Sec}, which is calculated by the AGC controller, considering various factors and considerations. Following the computation, this reserve power is effectively allocated and dispersed among the power system generating units using the suggested dispatch technique. Within this study, additional reserve power has been utilized from TGSs (ΔP_{TGS}) and WGSs (ΔP_{WGS}), respectively, along with limits of line loadings.

2.2. *Proposed Dispatch Strategy.*

Figure 2 illustrates the implemented dispatch strategy in the proposed AGC system. The ACE is precisely calculated when a system frequency deviation is detected at the initial stage. Subsequently, the AGC regulator analyzes this error and determines the necessary adjustment in reserve power (ΔP_{Sec}) to effectively address the detected deviation. This study efficiently

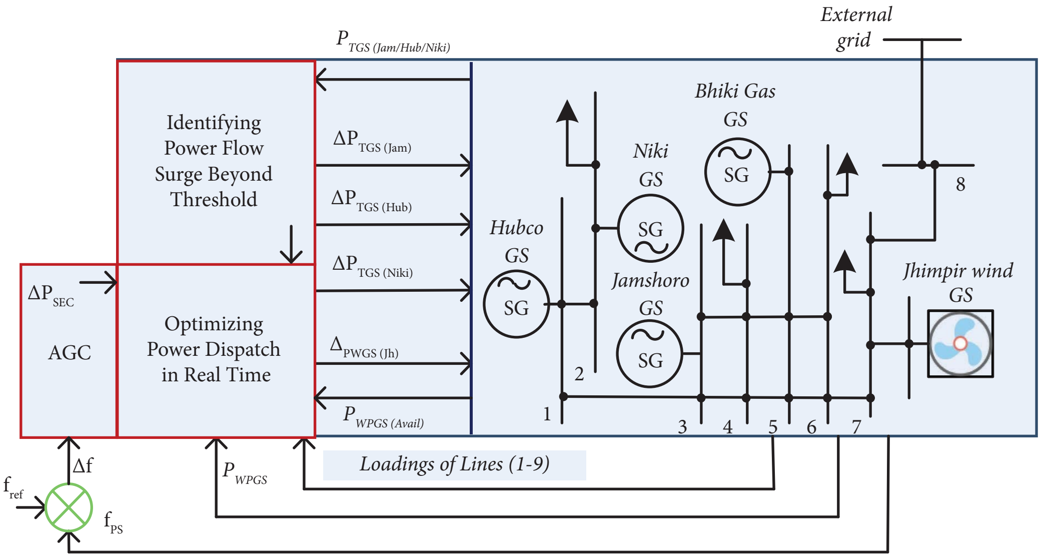


Figure 1: AGC system model for system operation.

Table 1: Pakistan power system network data.

B. no	GS (500 KV)	Associated lines (500 KV)
1	Niki (NKI)	HBC-NKI
2	Guddu New (GDN)	DU-GDN
3	Niki (NKI)	HBC-NKI
4	Hubco (HBC)	HBC-JMS, HBC-NKI
5	Dadu (DU)	SKP-DU (2), DU-DGK
6	Dadu-New (DUN)	DUN-SKP (2), JMS-DUN (2)
7	DG Khan (DGK)	DGK-EXT grid, DU-DGK
8	Jamshoro (JMS)	JMS-DUN (2), HBC-JMS
9	Shikarpur (SKP)	DUN-SKP (2), SKP-DU (2),
10	DG Khan (DGK)	DGK-EXT grid, DU-DGK

distributes the AGC response on the TGS generating units in scenarios demanding increased output. However, in cases where downregulation is needed, the AGC response is expanded to include both the TGSs and WGSs.

Wind energy undergoes exclusive curtailment under specific conditions in scenarios requiring downregulation dispatch. These conditions emerge when TGS units operate near their lower limits, at 22% of their maximum output, or when the dispatched power reaches the lower thresholds. This approach minimizes dependence on reserve power from TGSs and allows WGSs to operate at their maximum capacity. Simultaneously, all transmission lines' real-time power flow data are continually observed throughout the dispatch process. The recommended dispatch technique seamlessly engages in optimal dispatching if there are any indications of overloading on a line during this complex procedure.

This approach carefully assesses the effects of AGC dispatch on overloaded power lines. This strategy effectively addresses and resolves the issue by identifying transmission lines with load factors exceeding a set threshold, known as target heavy load lines. To prevent the potential harm of overloading on the target lines, the AGC system adjusts its dispatching ratio highly efficiently. This detailed process involves determining the excess power amount and then proportionally reducing the power dispatch of the relevant energy systems. Concurrently, additional power is injected into the grid by increasing the dispatched power from the local bus directly connected to the congested line. By coordinating these intricate actions, the designed AGC system manages the ACE while simultaneously ensuring the reliable protection of the complex transmission systems. However, in specific situations where line loadings go unnoticed by the monitoring mechanisms, the dispatching ratio remains fixed at a constant value precisely matching the generation capacity ratio. Line loading refers to the excess power flow exceeding the observant system operator's predetermined threshold. The estimated or threshold value for line loading is firmly established at 90% in the present investigation. Consequently, if the power flow in a particular line exceeds 90% of its total capacity, it is labelled as a loaded line requiring immediate attention. The accurate measurement of line loading for each transmission line is meticulously achieved through the application of a carefully derived equation, which is as follows:

$$\text{Line Loading} = \frac{\text{Line Actual Current}}{\text{Line Current Rating}} \times 100. \tag{3}$$

2.3. Power Plant Modelling

2.3.1. Thermal Generation System. The study adopts a unified approach utilizing the combined TGS framework to effectively provide the required extra power during the supply demand balance, in tandem with the routine operations within the power grid. The comprehensive response of the TGSs relies on the complex interaction of the boiler, significantly influencing the system's overall stability and operational dynamics. To illustrate this connection, Figure 3 introduces TGSs designed and streamlined for extensive long-term dynamic simulation studies. The model highlights

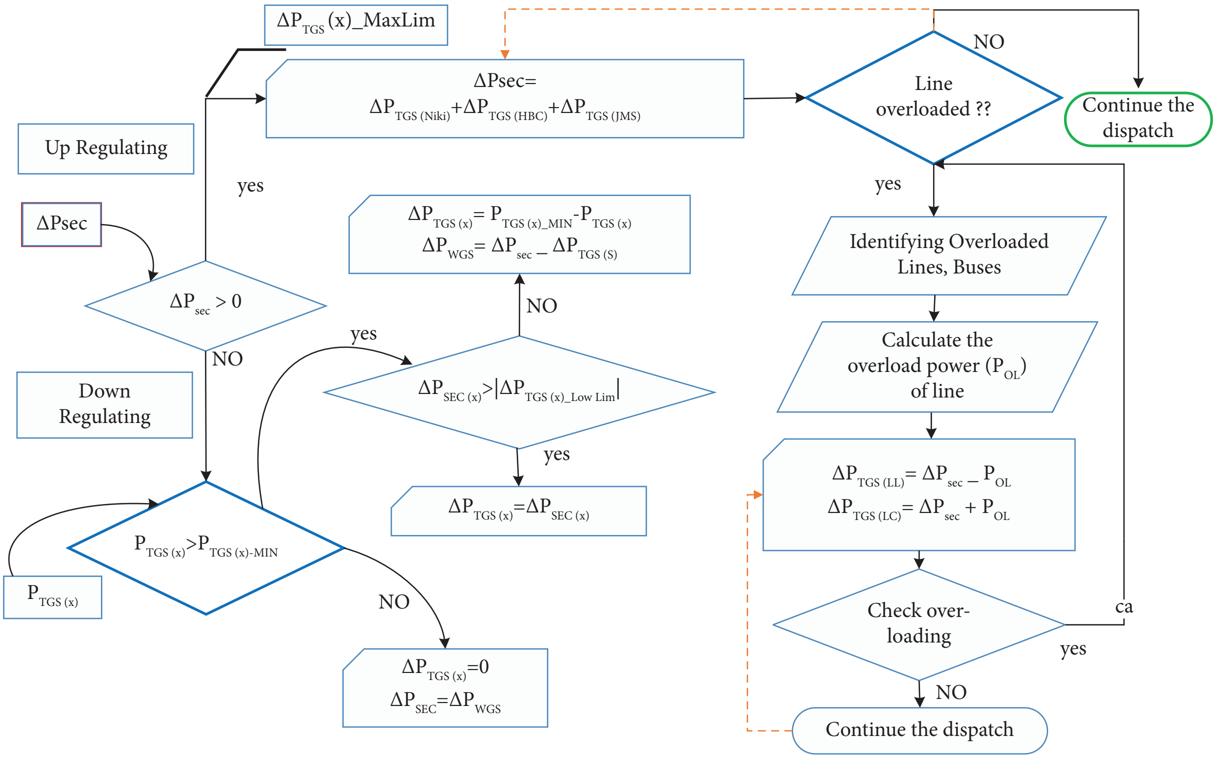


Figure 2: Proposed AGC dispatch strategy.

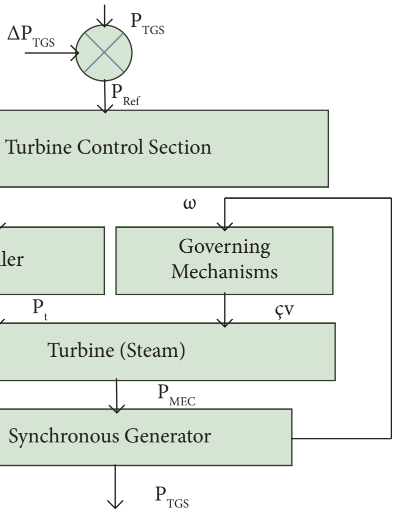


Figure 3: Thermal generation system.

the crucial role of the steam turbine block in supplying essential mechanical output power (P_{mech}). This is achieved through its interactions with two critical components: the governor section (cv) and the steam pressure section (P_t) originating from the boiler section.

Importantly, L_R acts as a vital factor for the boiler control part, changing dynamically when encountering load variations. These variations are effectively counteracted within a unit of boiler through a recalculation of the mainstream pressure value (P_t), accounting for the inherent limitations imposed on the output rate of the turbine and the associated delays stemming from the stored steam energy within the boiler. Moreover, the nonlinearity influence is effectively achieved by incorporating a ramp rate limitation set at 30 MW/min. By considering and integrating these factors, the study establishes a comprehensive model that accurately represents the behaviour and dynamics of the TGSs, facilitating deeper understanding and more informed decision-making processes in power system operations.

The governor governs the turbine speed valve regulation and provides the primary response. This involves adjusting the turbine speed valves in direct response to changes in

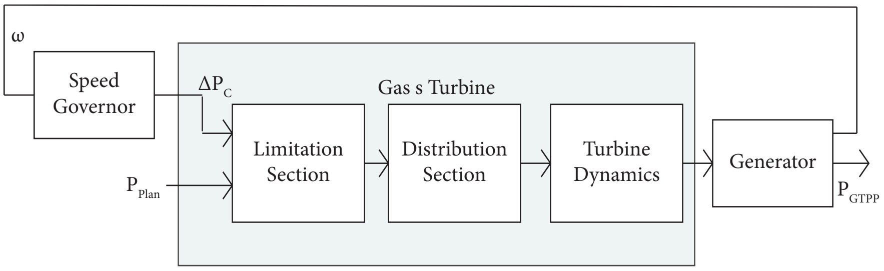


FIGURE 4: Gas turbine generation system.

generator speed and the governor droop setting. For this study, the droop setting is firmly set at a constant level of 3.45%. Dead bands are considered while designing governors to ensure system stability and circumvent fine-tuning. These dead bands act as a restraint, obstructing the activation of the steam valve for negligible speed deviations attributable to mechanical malfunctions. Within the system design, a consolidated steam storage block, denoted as b_1, b_2, and P_t, assumes an important role. These modules ingeniously encapsulate steam storage dynamics within the boiler while considering the internal pressure fluctuations. Furthermore, the boiler model incorporates time constants, denoted as T_{b1}, T_{b2} and T_{b3}, which introduce measured delays within the system. These time constants epitomize the characteristic response times of the boiler, with empirical evidence suggesting that they typically fall within the range of 5 to 6 minutes. This investigation examines a double reheat and cross-compound steam turbine, as depicted in Figure 3. The overall response of the turbine is encapsulated within four distinctive time constants, denoted as T_1, T_2, T_3, and T_4. These time constants intricately capture the dynamic interactions in charging various volumes, such as the high-pressure turbine bowls, reheater time constant, crossover, and double reheat units. In this complex system, a series of coefficients labelled as $K_1 - K_8$ precisely denotes the unique contribution of each section.

2.3.2. Gas Turbine Generation System. This study primarily centres around the synthesized framework of a gas turbine power plant, specifically analyzing its pivotal role in delivering primary response during power equilibrium. Figure 4 presents the model that encompasses a multitude of fundamental components, including a power limitation block (PLB), power distribution block (PDB), and gas turbine dynamics block (GTDB). It incorporates a low-pass filter and a dead band to enhance the functionality, effectively managing high- and low-frequency variations. In the presence of load fluctuations, deviations arise in the frequency, which is transformed into a power demand signal (ΔP_c). This ΔP_c signal acts as input to the PLB, where physical constraints are applied to regulate the response of the gas turbine. Furthermore, this block refrains the reference signal within the upper bound of $P_{\max}$ and the lower bounds of $P_{\min}$. Moreover, this block also incorporates upper load reference set points $L_{\max}$ and lower load reference set points $L_{\min}$ to ensure compliance with combustion constraints. A rate limiter block is implemented to address the challenges of rapid power demand changes.

The CLC signal is conveyed to the PDB section, which comprises two chambers functioning consecutively. In the EV compartment, pressurized air functions as the input and undergoes warming before blending with a ratio equal to half the total fuel allotment. The resulting amalgamation is introduced into the turbine with high pressure, initiating its rotation and mitigating the pressure. The residual 50% of the fuel portion and supplementary air inflow are combined with the aforementioned mixture in the SEV chamber. Subsequently, this unique combination is expelled through the low-pressure turbine, initiating its rotational motion. This designed operational procedure ensures exceptional operational flexibility, minimal emissions, and remarkable efficiency. The overall output of the gas turbine is influenced by different sections of the turbine, including CFM, CEV, CSEV, CVGV, and CLC, and it provide ouput within the limits of $P_{\max}$ and $P_{\min}$.

2.3.3. Wind Generation System. The investigation has undertaken the WGS modelling to analyze its performance during the power system operations, encompassing the provision of regulating reserves and the system's nominal operation. The formulated model is developed to function at the grid level, considering the cumulative influence of many wind turbines rather than concentrating on the individual efficacy of a particular wind farm.

Figure 5 illustrates the complex composition of the WGSs, prominently showcasing three crucial blocks: the wind generation system active power controller (WGSAPC), the wind turbine active power controller (WTAPC), and the generator reference current block. $P_{\text{ref\_WT}}$ signal is a complex function incorporating P_{ref}, the output of the governor (ΔP_c), and the measured power at the point of common coupling ($P_{\text{meas}_{-\text{PCC}}}$). The governor model takes into account the impact of dead bands, ensuring the provision of the necessary change signal (ΔP_c), which is based on the signal from the droop unit and the $P_{\text{meas}_{-\text{PCC}}}$ Unit. Within the WGSAPC block, the PI controller assumes the responsibility of regulating the P_{ref} signal, making adjustments based on the disparity of the $P_{\text{ref\_WGS}}$ and $P_{\text{meas}_{-\text{PCC}}}$ signals. The resultant power of the PI regulator is limited by the signal derived from $P_{\text{WGS}_{\text{avail}}}$. In tandem with the reference signal furnished by the WGSAPC block, the WTAPC block generates the current active component, represented as I_{Pcmd},

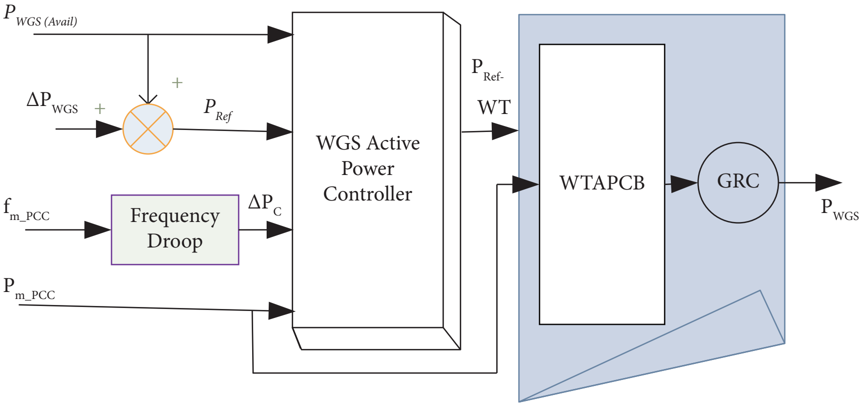


Figure 5: Wind power generation system.

which is computed through the PI controller. The determination of I_{Pcmd} hinges on the distinction between $P_{\text{ref\_WT}}$ and $P_{\text{meas\_PCC}}$ signals. The article investigates wind turbine applications based on type IV, which provides the necessary operational versatility. This technology separates the MSC and the GSC to fulfill their respective functions. The former is accountable for rotating the generator at a precise velocity. On the other hand, the GSC regulates the power flow to the grid. The wind turbine employs a static generator that incorporates a current source model. The interaction of inputs derived from the PLL and the current reference signal shapes the static generator response. In addition, to regulate the value of the reference, limitations on ramp rate are employed, considering the attainable wind power. Notably, WGS demonstrates unparalleled agility, exhibiting the swiftest response time among its power plant counterparts when confronted with fluctuations in system loads. This responsiveness is typically observed within a timeframe spanning 2 to 4 seconds.

3. Simulation and Results

The previous section introduced the AGC model for the power system alongside a dispatch strategy designed to address the possibility of transmission line overloads in the power dispatch process. These measures serve to optimize power balancing operation. This section undertakes the implementation of the dispatch strategy and conducts a thorough analysis of the resulting outcomes. To effectively carry out this analysis, a theoretical network representing the power grid of Pakistan has been modelled, with specific emphasis placed on a carefully selected portion of the system. The chosen network segment embodies a 5-machine, 8-bus configuration interconnected through 500 KV transmission lines, modelled in the DIgSILENT PowerFactory software. This network incorporates various generation systems positioned at different bus locations. This network integrates three TGSs, GTGSs, and a WGS system. The generating units housed within these TGSs, GTGSs, and WGSs deliver primary reserves to meet the power system demands. In a synchronized fashion, reserves at the secondary level are provided by the TGSs and WGSs, conforming to the designated dispatch strategy. Moreover, to comprehensively examine power fluctuations, the proposed power grid is integrated with an outside grid that matches the distinctive attributes of a grid system, showcasing an impressive frequency response (primary) of 6000 MW/Hz, accompanied by a noteworthy inertia of 16 seconds.

To grasp the operational dynamics of the envisaged AGC model, the investigation has utilized the real-time input series for the energy system and integrated load. Furthermore, a scenario is being developed and implemented to analyze the congestion problems during the dispatch process. The current operating scenario is presented in Table 2, depicting the varying active points of the generating units aimed at meeting the daily load demand. It is noteworthy to highlight that, in this study, the line loading limit is established at 90%. This implies that if the loading of any line surpasses this threshold value, that line will be deemed a loaded line.

The power capacities and operating reserves of the generating units and integrated loads remain constant, as elucidated in Table 2. Additionally, Figure 6 illustrates the initial power generations, comprising three units of thermal energy systems, a gas turbine unit, and a wind generation plant unit. Notably, the TGSs and the WGSs contribute their power to the ancillary services to keep the energy balance between load demand and generation, which arises due to the associated forecast errors.

Figure 7 portrays the initial disparity in power between electricity demand and generation, stemming from wind power generation forecasting error. These imbalances must be rectified using operating reserves from WGSs and TGSs at various bus stations. All TGSs actively provide positive and negative regulation reserves within this specific scenario, while the WGSs exclusively handle negative power imbalances. Simultaneously, the power flow across transmission lines is continuously monitored through load flow analysis in accordance with the developed dispatch strategy. When any transmission line exceeds the predetermined threshold for line loading, the AGC regulator optimizes the dispatch ratio to alleviate the strain on the overloaded lines. This objective is accomplished by strategically decreasing the

Table 2: Initial conditions, control reserves, and operational reserves of generating units.

Power plant models	TGS (Jamsh)	TGS (Hub)	TGS (Niki)	GTGS (Bhiki)	WGS (Jhpr)	LD (Jamsh)	LD (Niki)	LD (Dadu)	LD (Guddo-New)
Generation	1299	1301	759	222	2834	—	—	—	—
Reserves	±100	±103	±121	0	−500	—	—	—	—
IOP	1110	1031	400	218	2525	2930	865	698	1212

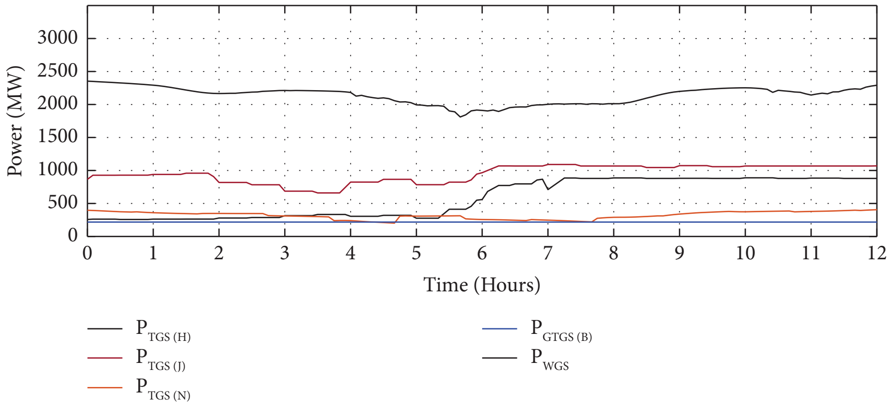


Figure 6: Power generation of power plant units.

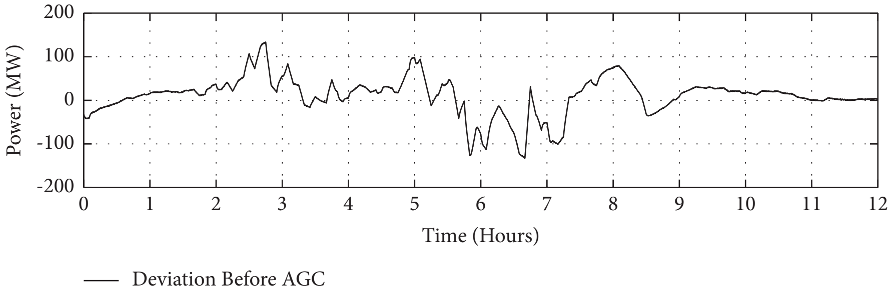


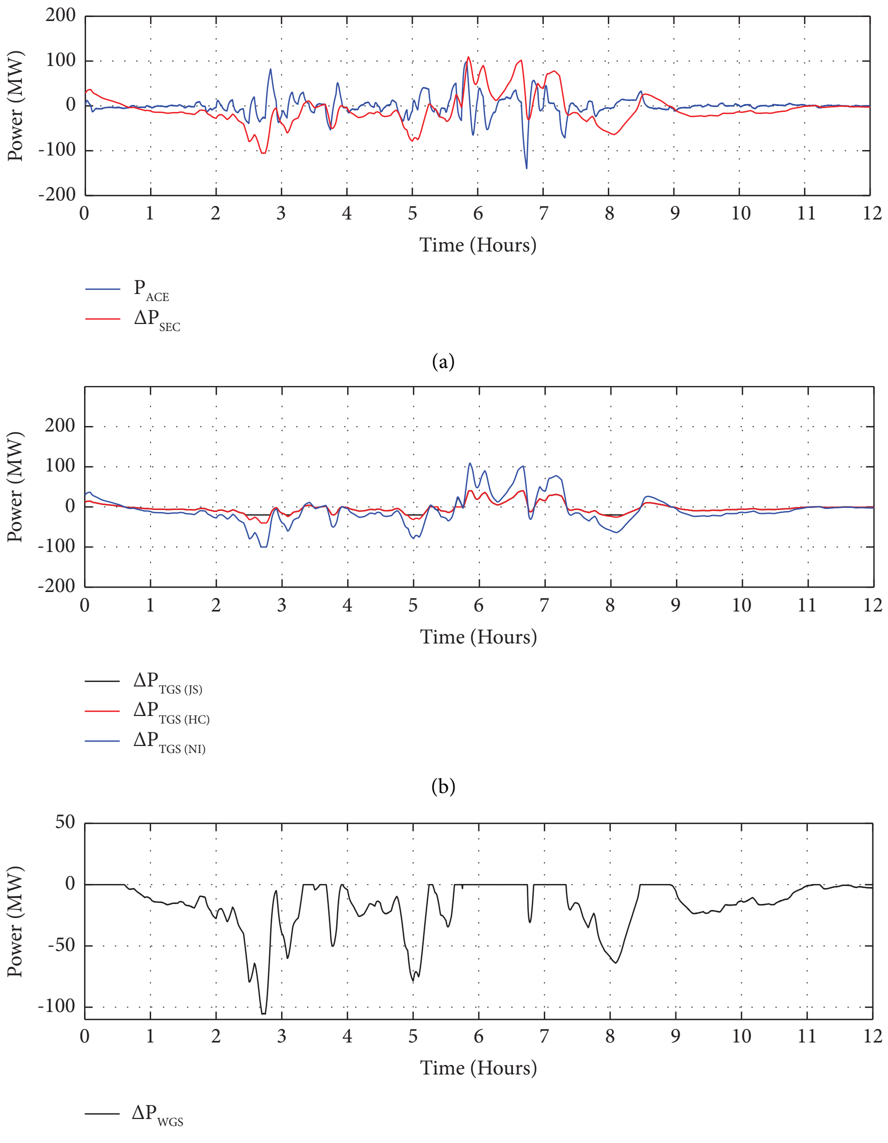
Figure 7: Power variations due to WES intermittencies.

generation output of the respective generating systems. The power generation adjustment is tailored to alleviate the strain on the overloaded lines, ensuring an optimal balance between supply and demand.

In addition, any extra power generated is sent to the grid through the local bus connected to the overloaded line. Conversely, in the absence of any line exceeding the predetermined load threshold, the dispatch division will remain unaltered, maintaining the identical allocation witnessed in the preloading impact state. The threshold value is finely tuned to 90% of the overall line capacity to ensure the efficient and dependable operation of the transmission network.

Figure 8 presents the performance of all generating units throughout a simulated duration of 12 hours as they deliver the essential reserve power during AGC operations. The figure demonstrates the active engagement of TGSs in providing up and downregulation reserves, whereas the WGSs exclusively contribute to providing the negative regulating reserves. This arises due to the cost-effectiveness of the WGS, which typically operates at its maximum capacity. Nevertheless, the generative potential of the WGSs experiences a noteworthy decline upon the convergence of all TGSs near their minimum operational threshold ($P_{\text{TGS},\min(x)}$), established at a mere 20% of their maximum capacity, or when the allocated power to all TGSs reaches their lowermost limits. Under such circumstances, the TGSs would lack adequate reserves to sustain the grid's stability. As a result, the WGS gradually decreases its output power to regulate P_{ACE} per network's requisites.

As part of the power balancing operations, the dispatch mechanism incorporates the capacity limitations of transmission lines to prevent any potential overloading problems. To achieve this, secondary reserves are mobilized from generating units that do not impose strain on the associated transmission line system. Figure 8 visually represents the dispatch power distribution, highlighting that the Niki generating unit has the highest dispatch power. In contrast, the Jamshoro generating unit has the lowest dispatch power. Moreover, the initiation of reserves from the Hubco energy



(a)

(b)

(c)

Figure 8: (a) AGC dispatch following ACE. (b) Individual dispatch from TGSs (Jamsh., Hubco, and Niki). (c) WGS (Jampir).

system is minimal, guaranteeing optimal resource utilization while upholding system stability. The prevailing circumstance arises from the transmission line interconnecting the Hubco and Niki grid stations operating at their utmost capacity. Any additional dispatch originating from the Hubco grid or other interconnected stations carries the potential risk of overburdening this specific transmission line. However, the nearby Niki bus station's generating facility effectively compensates for the needed regulatory power. The efficacy of the AGC operation becomes evident through the response exhibited by all network lines, as portrayed in Figure 9, wherein each line operates well within the prescribed maximum loading threshold of 90%. Remarkably, the connection between the Hubco and Niki grid stations consistently functions at its highest capability, thereby imposing limitations on the dispatch capabilities of the installed generating units at the respective bus stations, constraining their output to lower levels.

Figure 10 presents the system frequency response and fluctuations noted in the AC interconnection. The illustration underscores the successful management of the system frequency, ensuring stability at the specified level throughout the entire period. The AGC system effectively manages and adjusts the frequency at different intervals to maintain it within the desired range. This achievement is attributed to the activation of operating reserves whenever they are required. After implementing the AGC response, substantial reductions in power deviations are observed within the external grid. It is significant to mention that these residual discrepancies in the external grid represent the final deviations that endure within the system after the response of the AGC.

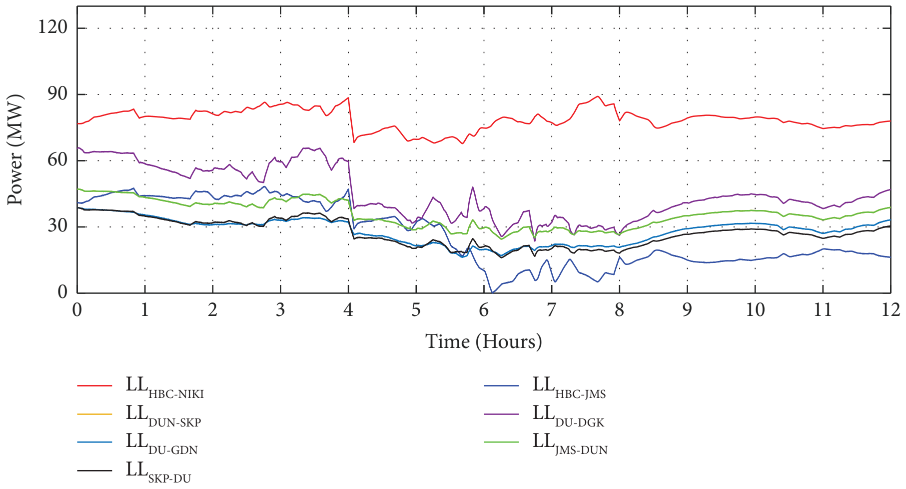
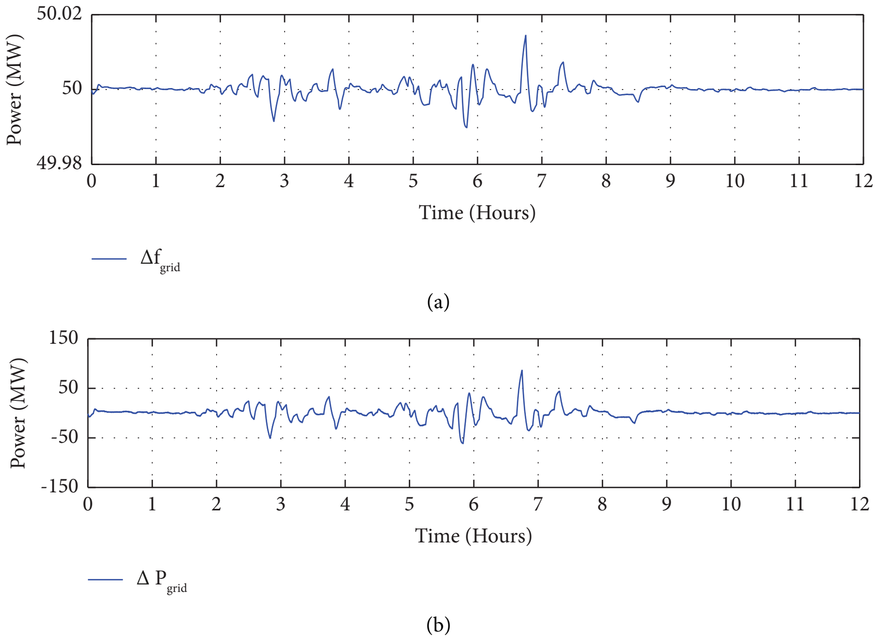


Figure 9: Line loading status after the AGC response.



(a)

(b)

Figure 10: (a) Power network frequency and (b) resulting power imbalances following AGC response.

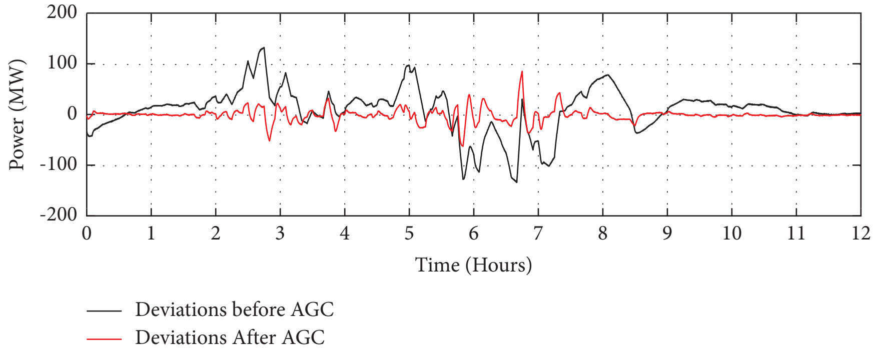


Figure 11: Comparing initial and final deviations after AGC response.

TABLE 3: Quantitative analysis of initial and final power imbalances.

Case studies	PR area (MW)	NR area (MW)	$\Delta_{\epsilon PR}$ (%)	$\Delta_{\epsilon NR}$ (%)
Initial error ($\epsilon_{\text{initial}}$)	3.876	3.060	0	0
CS-01	0.387	0.499	90.0	83.6

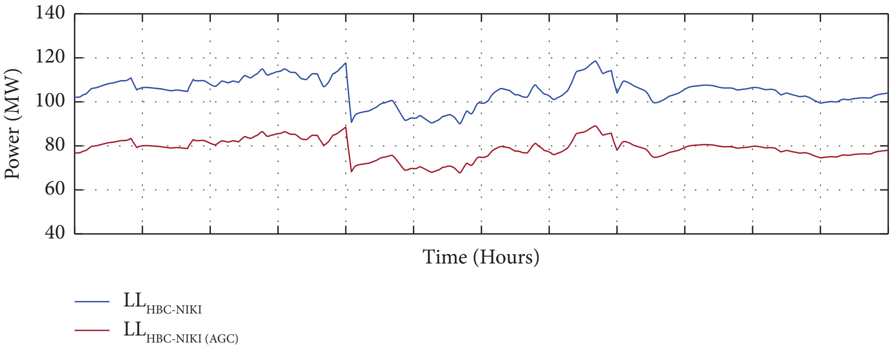


FIGURE 12: Comparative analysis of power loading on overloaded lines in AGC operations.

Figure 11 exemplifies the contrasting aspects between the initial and final power imbalances resulting from implementing the AGC response within the network. The graph exhibits a significant reduction in the initial power imbalances after triggering the operating reserves from energy systems' generating units.

Moreover, the study also conducted a quantitative analysis, as given in Table 3, in which the percentage of error reduction before and after the AGC response was given. Table 3 presents a detailed comparison, highlighting the quantitative differences between the initial and final power imbalances. The first row presents the initial positive and negative errors due to the power imbalance between the load and demand. Subsequent rows present the respective amounts of positive and negative errors observed in the network in different case studies. Positive and negative errors, in this case, are represented by the area under the curve, which has been carefully calculated to indicate the magnitude of imbalances.

Similarly, $\Delta_{\epsilon PR}$ represents the percentage error that has been reduced in the positive error and $\Delta_{\epsilon NR}$ represents the reduction in the magnitude of negative error. The equations for them are given as

$$\Delta_{\epsilon PR/NR} = \left(\frac{\epsilon_{\text{initial}} - \epsilon_{\text{case study (ith)}}}{\epsilon_{\text{initial}}} \right) \times 100. \tag{4}$$

Figure 12 comprehensively analyzes the power loading on the previously congested transmission line throughout the AGC operation. The graph visually portrays a substantial mitigation of the excessive power on the once-overburdened line, maintaining it below the predetermined threshold value of 90%, as stipulated within the confines of this research work. Consequently, it can be discerned that the suggested AGC dispatch approach adeptly executes the AGC process, upholding the utmost integrity of the transmission lines interwoven within the network.

4. Conclusions

Modern power systems require sophisticated control systems to keep the frequency and voltage within the allowable limits defined in the grid codes. Pakistan's power system is undergoing significant changes regarding incorporating renewable energy sources on a large scale. However, bulk integration of the RES into conventional grids increases the risk of uncertainty due to the forecasting errors associated with these sources and results in substantial power flow fluctuations. The conventional dispatch mechanism does not consider the constraints of the transmission lines and often results in the overloading of the transmission lines. Furthermore, operating reserves are integrated only from the conventional generating units, which further increase the operational cost of the system. This study has attempted to develop an automatic power dispatch system (AGC) for the Pakistan power system to automate the dispatch of the generating units by incorporating transmission line capacities into the dispatch to avoid line congestions and integrating wind power as operating reserves along with conventional generating units to increase the economic operation of the system. For simulation, a five-machine model with eight buses has been developed in DIgSILENT PowerFactory software, replicating the characteristics of the Pakistani power system. A real-time dynamic dispatch study has been developed and implemented on the developed model to show the suggested AGC design's effectiveness in alleviating transmission line congestion during routine power balancing operations. Furthermore, by incorporating wind energy as operating reserves in the designed AGC system, the generating units have been enabled to function in an economically optimized fashion, fostering cost-effectiveness and improving the overall performance of the power system.

The study can be extended to an AI-based AGC system, where the grid parameters can be forecasted more accurately, thereby reducing the forecasting error. Ultimately, RES sources can be massively integrated with proper line management techniques.

Nomenclature

GTGS:	Gas turbine generation system
GENCOs:	Generation companies
DISCOs:	Distribution companies
IOP:	Initial operating point
CLC:	Signal of command load
CIGRE:	International Standards for Power System
TGS:	Thermal generation system
CFM:	Baseload function
WGS:	Wind generation system
NTDC:	Service provider
NEPRA:	Regulatory body
GRC:	Grid side converter
CSEV:	Sequential environmental burner capacity
PDB:	Power distribution block
GTDB:	Gas turbine dynamics block
GRC:	Generation rate constraints.

Data Availability

The data used to support the study's findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

K.U., Z.U., B.S., and M.A. were responsible for conceptualization. K.U., M.I., S.S., and H.W. were responsible for data curation. Z.U., B.S., and M.A were responsible for formal analysis. B.S., M.I., and H.W. were responsible for investigation. K.U. and S.S. were responsible for methodology. Z.U. was responsible for project administration. B.S. and M.A. were responsible for resources. K.U. was responsible for software and supervision. Z.U., M.A., and H.W. were responsible for validation. B.S., M.I., and S.S. were responsible for data visualization. K.U., B.S., M.I., and M.A. were responsible for original draft preparation. Z.U., S.S., and H.W. were responsible for review and editing. Every contributor has thoroughly examined and endorsed the finalized manuscript for publication.

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