

Article

Line Overload Alleviations in Wind Energy Integrated Power Systems Using Automatic Generation Control

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Abstract: Modern power systems are largely based on renewable energy sources, especially wind power. However, wind power, due to its intermittent nature and associated forecasting errors, requires an additional amount of balancing power provided through the automatic generation control (AGC) system. In normal operation, AGC dispatch is based on the fixed participation factor taking into account only the economic operation of generating units. However, large-scale injection of additional reserves results in large fluctuations of line power flows, which may overload the line and subsequently reduce the system security if AGC follows the fixed participation factor's criteria. Therefore, to prevent the transmission line overloading, a dynamic dispatch strategy is required for the AGC system considering the capacities of the transmission lines along with the economic operation of generating units. This paper proposes a real-time dynamic AGC dispatch strategy, which protects the transmission line from overloading during the power dispatch process in an active power balancing operation. The proposed method optimizes the control of the AGC dispatch order to prevent power overflows in the transmission lines, which is achieved by considering how the output change of each generating unit affects the power flow in the associated bus system. Simulations are performed in Dig SILENT software by developing a 5 machine 8 bus Pakistan's power system model integrating thermal power plant units, gas turbines, and wind power plant systems. Results show that the proposed AGC design efficiently avoids the transmission line congestions in highly wind-integrated power along with the economic operation of generating units.

Keywords: automatic generation control; wind energy; transmission line security; dispatch strategies; Pakistan power system



Citation: Ullah, K.; Basit, A.; Ullah, Z.; Asghar, R.; Aslam, S.; Yafoz, A. Line Overload Alleviations in Wind Energy Integrated Power Systems Using Automatic Generation Control. *Sustainability* **2022**, *14*, 11810. <https://doi.org/10.3390/su141911810>

Academic Editor: Nien-Che Yang

Received: 24 August 2022

Accepted: 15 September 2022

Published: 20 September 2022

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1. Introduction

Wind power plants are directly connected to various voltage levels of power systems and the majority provide a sustainable connection to high voltage transmission grids. However, wind power is highly reliant on intermittent wind speed that incurs stochasticity and inaccurate accuracy, resulting in forecasting errors [1]. The forecasting errors of wind power have pertinent effects on power system operations by incurring a mismatch between supply and load demand that leads to deviation of generation and power exchanges from their scheduled values. The power system planners employ various scheduling mechanisms to deploy the extra amount of reserve, keeping the power grids in a balance condition. Conventionally, the additional reserves are provided manually or through automatic generation control (AGC) considering only the economic operation in the account [2]. As

a result, large fluctuations in the line power flow occur, which subsequently increases the risk of transmission lines overloading during the power balancing operation [3–5]. This may further deteriorate the power system security and causes permanent damage to the transmission line network. Contrarily, if enough margin capacity for the fluctuation running is set up in the transmission lines, the available capacity for the energy market transactions is reduced and high economic losses can occur. Therefore, the overloading of the transmission line network is becoming a serious problem threatening the stable operation of the power system in large-scale wind energy-based power systems.

The problem has been highlighted in several research articles [6–8]. In this regard, a comprehensive review of the deployment of AGC for conventional and modern power systems is proposed in [9]. Similarly, the integration of wind and electric vehicles in power systems is studied using the AGC strategies [10]. Various models are developed and implemented [11,12] in different kinds of electricity markets to alleviate the line overload in the massive renewable integrated power systems. Two broad models are normally used for the alleviations of line overloads, namely cost-free means and not-cost-free means. The cost-free means included actions like outraging of congested lines or operation of FACTS devices because the marginal costs (and not the capital costs) involved in their usage are nominal. The not-cost-free means include the re-dispatching of the generation amounts by backing down some generators while others increase their output and, as a result, the generators no longer operate at equal incremental costs. This study has explored the latter model, in which the dispatched power from the generating units is rescheduled to minimize line congestion. The authors in [13] proposed an enhanced power flow management scheme for the renewable energy-based power system to avoid transmission line overload during maximum power flow fluctuations. The study illustrated a detailed dispatching mechanism for the AGC system to reschedule the power flow in the heavily loaded line, utilizing the remained capacity of light-loaded lines, which act as a buffer of fluctuating power. However, the proposed AGC model does not operate effectively in the case when all lines are set to target, since the model is based on the utilization of the capacity of the light-loaded line. The authors in [14] used a direct method to reschedule the generation of the power plant units, alleviating the line overloads after any N-1 contingencies. In this method, the power at the receiving bus of the overloaded line is appropriately modified by an amount equal to the overloaded power during each iteration of the load flow solutions. However, the method uses a hit-and-miss procedure to measure the correct bus power adjustment and, therefore, consumed enough time.

Non-linear programming methods are employed in several research articles to find a coordinated control action to eliminate the transmission line overload in renewable integrated power systems [15,16]. The authors in [17] utilized a learning machine learning approach with classical constraints for the economic dispatch model to tackle the problem of line overload alleviations. In [18], an economic dispatch model was developed for the generating units based on the direct acyclic graph (DAG), which provides an optimal remedy for the large network having different interconnected areas. The study in [19] proposed a dispatch model for line overload alleviation, utilizing a technique based on mixed linear programming to minimize switch opening as a solution to reduce overloads. The authors in [20] reduced the overloading of the transmission lines using a fuzzy logic model that tried to recreate the network operators' actions; however, the generation cost has not been considered. In [21], the authors used the metaheuristics of fuzzy logic and genetic algorithm for the implementation of online economic dispatch that assisted the overload study by eliminating the modeling of the entire AC system and the difficulties of the non-convergence of exact solution approaches. The authors in [22] employed fractional order integral control for AGC of a multi-source interconnected power system. The research work in [23] utilized a primal-dual interior point-based technique for the dispatch process of generating units. However, before executing the algorithm for a final solution, different stages of the simplification for the dispatch scenarios are deliberated, which are required to be executed in clusters. Such a process creates a direct impact on the scenario selection.

The aforementioned literature has tackled the overloading problem in a detailed manner. However, the studies lack a real-time dispatch strategy for the AGC system, taking into account the secure operation of transmission lines, along with the economic operation in a high wind integrated power system network. This paper proposes real-time load alleviation techniques for the AGC system by incorporating the line capacity constraints in the dispatch and scheduling process. The study analyzes the impact of the overloaded power on the transmission lines and proposes a dispatch strategy for the AGC system to keep the power fluctuation of the transmission line under the prescribed limits during the power balancing operation. Transmission lines having an anticipated load factor greater than the threshold value are selected as target heavy load lines. The overloaded power is reduced in the target lines by optimizing the dispatching ratio of the AGC system. This is done by calculating the amount of overloaded power and reducing the dispatched power of the target generating units by that amount. Meanwhile, the deficient power is injected into the grid by increasing the dispatched power from the local grid station of that overloaded bus. In this way, the area control error is regulated along with the protection of the transmission lines. However, if the line loadings are not detected, the dispatching ratio is set to be constant at the generation capacity ratio. Hence, the proposed dispatch strategy mitigates overloads of transmission elements after N-1 contingencies, ensuring the minimum risk of collapse in the massively penetrated wind power systems. To verify the efficacy of the proposed method, simulations are performed on Pakistan's 5-machine 8-bus power system model in Dig silent power factory software. The impact of the overloaded power due to a random change in the dispatch order is firstly analyzed and then the proposed method is implemented to de-overload the target lines.

The pertinent contributions of this work are as follows:

- The aggregated model of Pakistan's 5-machine 8-bus power system network is developed by integrating the 500 kV transmission lines and generating units of thermal power plants, gas turbines, and wind power plant systems.
- A model of the AGC system is designed and a dispatch strategy is developed to maximize or minimize the power flow increase among target lines at which power flow increase is detected.
- The dispatch strategy is designed by considering different constraints such as maximum, minimum capacities, and reserve availability of generating units and power capacities of transmission lines. Further, the system model is simplified to find quick solutions to contingencies issues. The proposed model of the AGC system is validated using the step input and the real-time data inputs.

The remainder of the paper is divided as follows: Section 2 presents the modeling of the power plant units, such as thermal power plants, wind power plants, and gas turbines. Section 3 describes the proposed model of the AGC system along with the objective function and the proposed dispatch strategy for the line overload in the power balancing operation. Section 4 validates the proposed AGC system by initially applying a step input and then a real data input. Finally, Section 5 includes a summary, recommendations, and possible future works in the proposed research domain.

2. Modelling of the Power Plant Generating Units

This section contains thorough information on the modeling of power plant units, such as thermal power plant systems (THPPs), gas turbine-based power plant systems (GTPPs), and wind power plant systems (WPPs). The governor, which is designed and installed on power plant systems, provides the primary frequency response from each power plant unit. In addition, a centralized AGC system is designed for a secondary response, which is discussed in the following section.

2.1. Thermal Power Plant Model

The study considers the aggregated model of the thermal power plant system to provide the required primary and secondary reserve power in the balancing process of

load and generation along with the routine operation in the power system network. The entire response of the THPPs is based on the response of the boiler influencing the system stability operation. Figure 1 presents the detailed diagram of the THPPs, which is modeled based on the investigation taken from the study [24,25] and is simplified for long-term dynamic simulation studies. It is illustrated from the diagram that the steam turbine block provides the required mechanical outpower (P_{mech}) based on the input from two blocks, which include the governor block (cv) and the steam pressure (P_t) from the boiler block. L_R represents the load reference set point, which is provided from the boiler control section and varies in response to any change in the system load. This change is counter in the boiler section by recalculating the mainstream pressure value (P_t), considering the real limitation of the turbine output and the associated delays of the store steam energy in the boiler. The load reference set point signal (L_R) is a feed-forward signal of the boiler regulating the turbine valve to match the current generation value with the reference value. Furthermore, the GRC and STC effects are integrated by considering a ramp rate limitation of 30 MW/min.

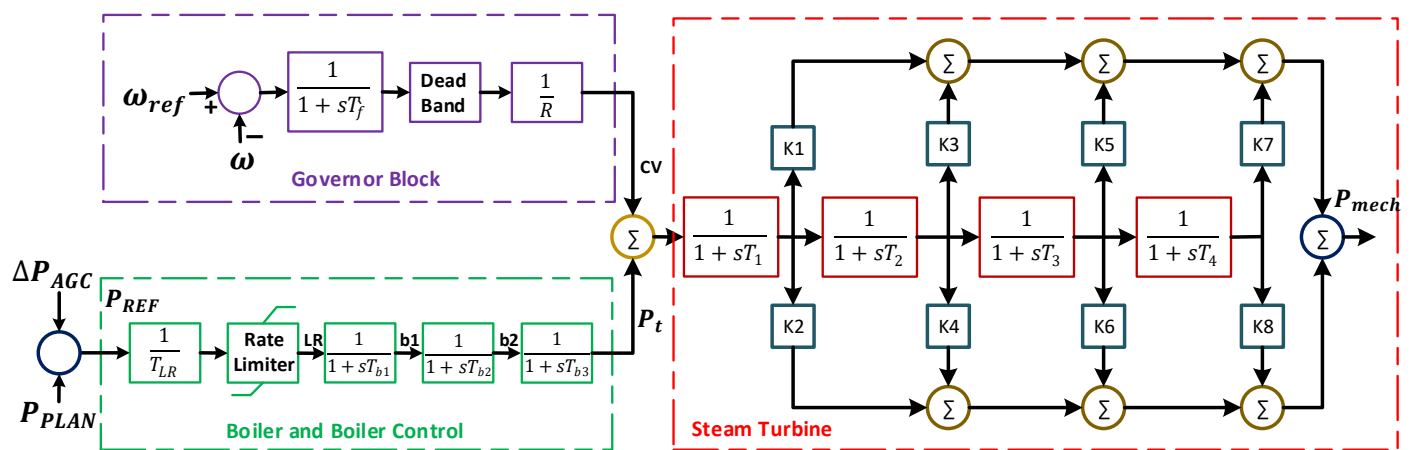


Figure 1. Thermal Power Plant Model.

The governor provides the required primary response by controlling the turbine speed valves based on speed variations of the generator and the droop setting of the governor. The droop setting in this study is fixed at 4 percent. Dead bands are added to the governor to prevent the motion of the steam valve from any small changes in speed due to the mechanical fault. b_1 , b_2 , and P_t are the corresponding lump storing steam series at interior pressure, while T_{b1} , T_{b2} , and T_{b3} are the associated time constants representing the time delays related to the boiler model. The response time of the boiler lies in the range of 5–6 min [26], leading to the overall response of the THPPs. This study considers a cross-compound double reheat steam turbine [24], as shown in Figure 1, which derives the output power in its mechanical form based on the inputs from the boiler model (P_t) and the governor output (cv). The four time constants (T_1 , T_2 , T_3 , and T_4) represent the overall response of the turbine, which characterizes the charging of various volumes including high-pressure turbine bowls and the time constant for re-heater, crossover, and double reheat units. $K_1 - K_8$ are different coefficients signifying the contribution of the turbine sections to the net mechanical output power. K_1 , K_2 represent very high pressure, K_3 , K_4 are only for high pressure, while K_5 , K_6 and K_7 , K_8 represent intermediate- and low-pressure contribution values.

2.2. Gas Turbine Power Plant Model

The gas turbine power plant aggregated model is being considered in this study to provide only the primary response during the power balancing process along with the daily routine operation. The developed model, as shown in Figure 2, is based on the study taken from [25–27], which comprises different blocks including the power distribution

block (PDB), power limitation block (PLB), and gas turbine dynamics block (GTDB). The governor model is designed for GTPPs integrating the low-pass filter and dead band effects to protect the model from responding to high frequency and low frequency variations, respectively. When there is any change in system load, the frequency of the system deviates from its original value, which is converted into a power demand signal (ΔP_c) by the droop characteristic signal. The resultant ΔP_c of the signal is provided as an input to the power limitation block, which utilizes the combustion technology physical constraints to impose physical barriers on the turbine response. The PLB block restricted the reference power signal to P_{max} and P_{min} , which are upper and lower power level limits. L_{max} and L_{min} are the upper and lower load reference set points in the PLB block, which ensure that no combustion constraints are violated during normal operation. A rate limiter block regulates the ramping of the power demand signal at a specific rate, preventing excessive fire during ramping up and the extinguishment of a narrow combustion flame during severe ramping down.

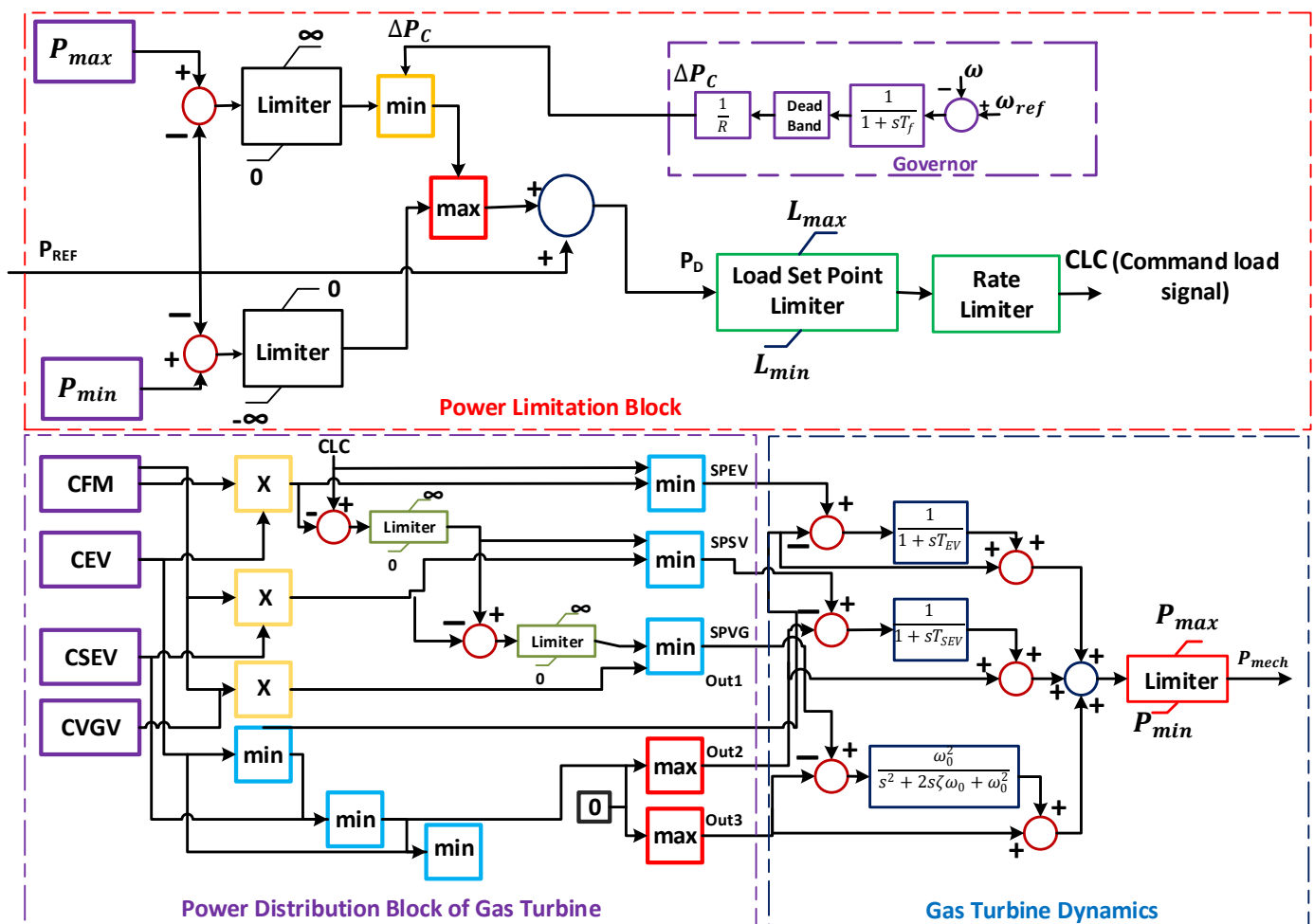


Figure 2. Gas Turbine Power Plant Model.

Command load signal (CLC) is the resultant signal generated by the PLB block, which is fed to the PDB block. The PDB block consists of two chambers fired in series. The EV chamber takes the compressed air as an input and mixes it with 50 percent of the total fuel after heating. Here, it is important to mention that the fuel flow is controlled through the CLC signal from the PDB block, while the airflow is controlled through the shaft speed and variable inlet guide vane (VIGV). The resultant mixture is entered into the high-pressure turbine, forcing it to spin, which causes the pressure to drop. The remaining 50 percent of the fuel and some additional air is added to the resultant mixture in the SEV

chamber. The new mixture is then expanded through the low-pressure turbine, forcing it to spin. This kind of procedure inculcates high operational flexibility, low emission, and high efficiency. The power contribution factors (CEV, CSEV, CVGV, and CFM) in the PDB control blocks represent the physical characteristics of fuel flow, airflow, and allowable temperature. The output of the power contribution factors depends on the CLC signal, air compressor, and the two combustors' capacities. The dynamics of the gas turbine dynamic block are represented by the compressor and combustor unit. The combustor EV and SEV are represented by the 1st order transfer function, while the variable inlet guide vane (VIGV) is represented by the 2nd order transfer function. T_{EV} and T_{SEV} are time constants for the burner of the EV and SEV combustors, respectively. The overall mechanical output of the turbine is a function of CFM, CEV, CSEV, CVGV, and CLC and is restricted between P_{max} and P_{min} .

2.3. Wind Power Plant Model

The study has modeled the wind power plant system to investigate its behavior during the active power balancing operation by providing the primary and secondary regulating reserves along with the normal system operation. The proposed model is developed to be operated at the power system level rather than considering the impact of a specific wind farm. This is because the aggregated performance of many wind turbines has a greater influence on the power system than the operation of a single turbine. The study considered the model proposed by the IEC61400-27-1 committee as the starting point for the model, drafted for the simulation models of wind power generation. Here, it is important to mention that the proposed model is developed for the control operation of the active power in the system, which is the focus of this study. However, the model includes all the relevant dynamics for long-term simulation studies. A detailed figure of the wind power plant system (WPPs) is shown in Figure 3, mainly consisting of three blocks, which are the wind power plant active power controller (WPPAPC), the wind turbine active power controller (WTAPC), and a generator reference current block.

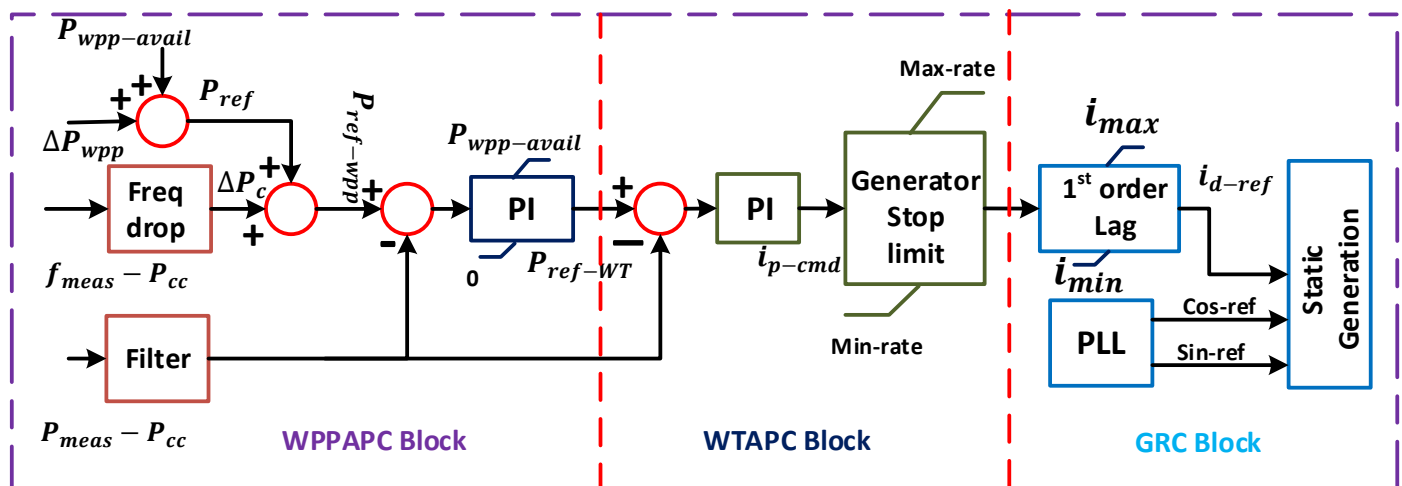


Figure 3. Wind Power Plant Model.

The WPPAPC block generates a reference signal at the wind turbine level (P_{ref-WT}) in response to any change in the reference signal at the wind power plant level ($P_{ref-WPPS}$). $P_{ref-WPPS}$ is a function of the reference signal (P_{ref}), governor output (ΔP_c), and measured power at PCC ($P_{meas-PCC}$). The governor model considers the effect of the dead bands and provides the required power change signal (ΔP_c) based on the droop characteristics signal and the available power strength. The PI controller of the WPPAPC block regulates its P_{ref} signal based on the difference between the $P_{ref-WPPS}$ and $P_{meas-PCC}$ signals. The signal of the $P_{WPP-avail}$ limits the PI controller output power. Following the reference signal from

the WPPAPC block, the WTAPC block generates the currently active component (I_{Pcmd}) as calculated by the PI controller and it is calculated based on the difference between the P_{ref_WT} and P_{meas_PCC} signals. This study considers the type IV wind turbine technology for the generator as being able to provide the required operational flexibility. Machine-side convertors (MSC) of such turbines are decoupled from the grid-side converter (GSC) to perform their tasks. MSC rotates the generator at a specific speed, while the GSC controls the active and reactive power flow to the grid side. The generator used in the wind turbine is modeled as a static generator considering the current source because grid-side wind turbine behavior is determined by the full-scale converter. The dynamic response of the static generator is a function of the inputs from the phase-locked loop (PLL) and reference current. In addition, a ramp-rate limitation is also added to limit the reference value based on available wind power. WPP has the fastest response time among the power plant units to any change in system loads, which is typically 2–4 s.

3. Power System AGC Model and the Proposed Control Strategy

This section presents detailed information about the proposed power system AGC model, followed by the objective functions and the proposed dispatch strategy implemented in the AGC system.

3.1. Power System AGC Model

The secure and reliable operation of the power system is determined by the automatic generation control (AGC), which continuously monitors the frequency of an interconnected power system and accordingly performs the remedy measures if required. In the AGC control, two variables determine the whole operation, which includes frequency deviations and the interchanged power. These two variables accumulatively make one equation called area control error (ACE), which is a prime step in the execution of the AGC control. The equation of ACE for an i^{th} area of an interconnected power system is given as:

$$P_{ACE,i}[MW] = \sum_{j \in \mathcal{A}_n} \beta_i \Delta f + \Delta P_{ij} \quad (1)$$

In the above equation, $P_{ACE,i}[MW]$ is the imbalance of power in the i^{th} area of the system following any change in the system load. Δf represents the deviations in the frequency, while β_i is the frequency bias constant of the i^{th} area. β_i is represented by the equation $\beta_i \left[\frac{MW}{Hz} \right] = D_i + \frac{1}{R_i}$, in which $D_i \left[\frac{MW}{Hz} \right]$ characterizes the damping of the power system, while $R_i \left[\frac{MW}{Hz} \right]$ is the droop characteristics. In this study, R_i is fixed at a 4 percent value. $\Delta P_{ij}[MW]$ is the total change in the interchange power, which is the difference between the actual and scheduled interchange power and is called the tie-line error. The system frequency instantly varies following any load change in the network due to which the primary reserves are activated through a governor installed on each generator unit. Meanwhile, AGC calculates the required area control error $P_{ACE,i}$ and releases the secondary reserves to regulate it and release the primary reserve. This process brings the frequency to its nominal level. In such a way, the AGC regulator maintains the frequency of the system at its nominal level and keeps the interchange power at its scheduled value by performing the minute-to-minute balancing in the i^{th} controlled area. The AGC operation time lies in the range of 1–10 min.

Conventionally, the AGC system regulates the area control error and tie-line interchanges, which is the only power flow control function. However, the power flow on the rest of the lines in the power system network is not regulated, which often results in the overloading of the transmission lines during the power balancing operation. The operation of AGC regulates the active power flow, which is absorbed or injected by different components of the power system. Therefore, overloading of the power lines can be avoided during the power balancing operation by considering the line limits in the AGC dispatch process. The focus of this study is to integrate the line capacities of the

transmission line system in AGC dispatch, which considers the line loading limits of all the lines before distributing the dispatching power to the generating units. Hence, the power fluctuation in the transmission lines is controlled by re-scheduling the participation factor of the generating units.

Figure 4 shows the network layout of the proposed power system AGC model. An 8-bus 5-machine model of Pakistan’s power system is considered in this study, consisting of different generating units of thermal power plants, gas turbines, and wind power plant systems. The generating units are connected to different buses of the 500 kV transmission system. Furthermore, to study the dynamics of the AC interconnection, an external grid is connected, emulating the characteristics of a general grid having an inertia of 16 s. It is important to mention that the unit of inertia utilized in this study is in seconds. This is because, in a per unit system, inertia is equivalent to energy per power, which means that the rate at which the power changes in the power system network is restricted. Moreover, the primary frequency response of the connected grid is 6000 MW/Hz, which means that the rate at which the external grid responds per Hz changes with system frequency. Detailed information on the connected buses and the associated lines is given in Table 1.

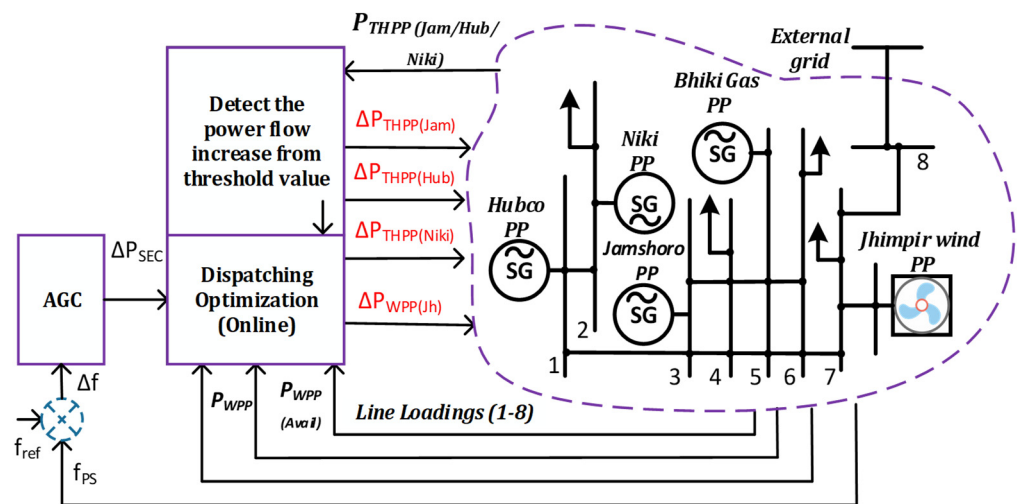


Figure 4. Proposed Power System AGC Model.

Table 1. Grid stations and associated lines of the network.

| S. No. | Grid Stations (500 kV) | Location (Pakistan) | Connected Lines and Dist. (500 kV) |
|--------|------------------------|----------------------|---|
| 1 | Niki (NKI) | North Karachi | HBC-NKI (63 km) |
| 2 | Shikarpur (SKP) | Shikarpur, Sindh | SKP-DU (2) (153 km), DUN-SKP (2) (159 km) |
| 3 | Dadu-New (DUN) | Sindh | JMS-DUN (2) (199 km), DUN-SKP (2) |
| 4 | Jamshoro (JMS) | Jasmshoro, Sindh | HBC-JMS (198 km), JMS-DUN (2) |
| 5 | Hubco (HBC) | Lasbela, Balochistan | HBC-NKI (63 km), HBC-JMS |
| 6 | Dadu (DU) | Dadu, Sindh | SKP-DU (2), DU-DGK (544 km) |
| 7 | Guddu New (GDN) | Kashmore, Sindh | DU-GDN (319 km) |
| 8 | DG Khan (DGK) | DG Khan | DU-DGK, DGK-EXT Grid |

The objective of this study is to alleviate the overloading of the transmission lines during the power balancing operation by considering the power capacities of the lines. Therefore, to simplify the complex model of transmission line systems to achieve the aforementioned objectives, this study has ignored the other parameters of the transmission line while performing this task. The other parameters include the line lengths and the line

voltages. Furthermore, the AGC implemented in this study considers a PI controller, which is used to minimize the P_{ACE} , as provided in (2).

$$\Delta P_{Sec} = K \cdot \Delta P_{ACE} + KT \int \Delta P_{ACE} dt \quad (2)$$

The values of the parameters K and T are necessary to restore the network's frequency and the interchange power to their original values. The values of these parameters are set following the conventional criteria for a coordinated secondary control system [28]. The activation rate of the reserves from the generating units of the power plants is characterized by the tracking speed of the controller known as the time constant. ΔP_{Sec} [MW] is the amount of reserve power calculated by the AGC controller to be distributed among the generating units utilizing the proposed dispatch technique. In this study, the extra amount of reserve power is utilized from different units of thermal power plants ($\Delta P_{THPP(JMS)}$, $\Delta P_{THPP(HBC)}$, $\Delta P_{THPP(NIKi)}$ [MW]) and the wind power plant (ΔP_{WPP}) [MW], considering all the constraints of the generating units and the transmission lines.

3.2. Objective Function and the Proposed Dispatch Strategy

The uncontrolled power flow in the transmission line of large-scale wind-integrated power systems replicate serious repercussions on the health of the transmission system. Power flow congestion management aims to alleviate the transmission line overload while lowering the generation cost. This is expressed mathematically as follows:

Objective No. 1:

$$\text{Min} \sum_{j=1}^{N_L} (\varphi_J - \varphi_{CP}) \quad (3)$$

Subjected to:

Equality Constraints:

$$P_{Gi} - P_{LDi} = \sum_{j=1}^{N_B} |V_i| |V_j| |Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (4)$$

$$Q_{Gi} - Q_{LDi} = \sum_{j=1}^{N_B} |V_i| |V_j| |Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (5)$$

Inequality Constraints:

$$P_{min} \leq P_{Gi} \leq P_{max} \quad (6)$$

$$Q_{min} \leq Q_{Gi} \leq Q_{max} \quad (7)$$

$$\Delta P_{min \text{ limit}} \leq \Delta P_{Gi} \leq \Delta P_{max \text{ limit}} \quad (8)$$

Figure 5 presents the proposed dispatch strategy for the developed AGC model as mentioned in Figure 4. Initially, when there is any change in the system frequency, area control error is calculated and based on that, the AGC regulator calculates the required change in reserve power (ΔP_{Sec}), which is then distributed among the different generating units to regulate the area control error (P_{ACE}). For positive regulation, the required AGC response is divided among the different generating units of the thermal power plant. However, the negative regulation wind power plant is also integrated into the AGC response along with thermal power plant units. In the event of a negative dispatch, wind power output is reduced only if all thermal power plants are running at their lower limitations, which are set at 20% of their full capacity, or if the dispatched power is approaching their lower limits. This reduces the use of reserve power from thermal generating units while allowing the wind power plant to run at full capacity.

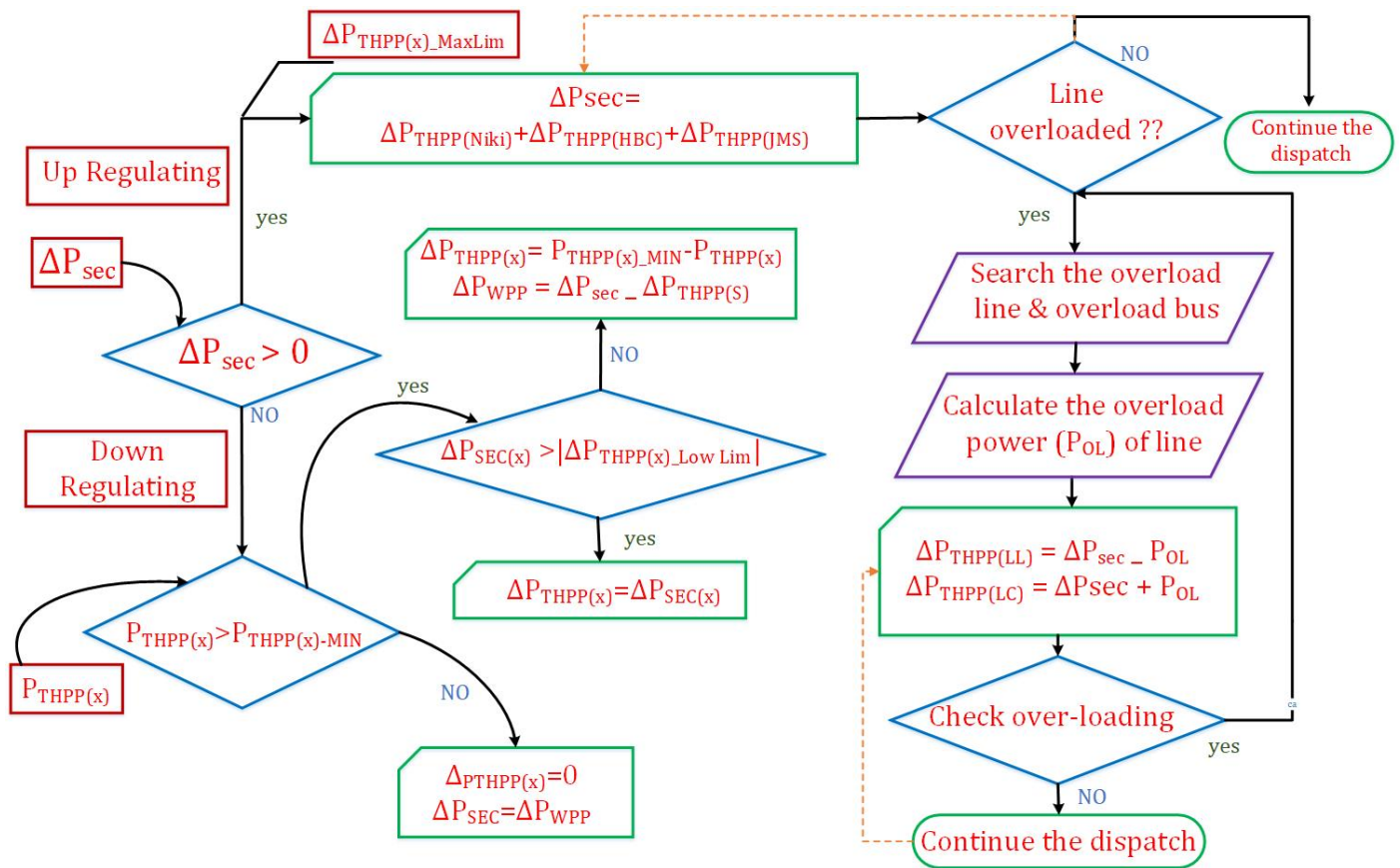


Figure 5. Proposed Dispatch Strategy for the AGC System.

Meanwhile, the line data of power flows in all the transmission lines are continuously measured during the dispatch process, and in case any of the lines are overloaded during the dispatch process, the proposed dispatch strategy performs the optimal dispatching, in which the impact of AGC dispatch on overloaded power flow lines are calculated. Transmission lines with an estimated load factor larger than the threshold value are chosen as target heavy load lines. Overloaded power is reduced in the target lines by adjusting the AGC system's dispatching ratio. This is accomplished by determining the amount of overloaded power and reducing the dispatched power of the target generating units by that amount. Meanwhile, inadequate power is injected into the grid by raising the dispatched power from the local grid station of that overloaded bus. In this way, the area control error is regulated along with the protection of the transmission lines. However, if the line loadings are not detected, the dispatching ratio is set to be constant at the generation capacity ratio. Here, line loading means an excess of power flow over a certain threshold value fixed by the operator. The estimated value or the threshold value of the transmission line loading is fixed at 90% in this study, which means that if a line exceeds its limit of 90%, it is considered a loaded line. The line loading of each transmission line is measured using the equation given as:

$$\text{Line Loading} = \frac{\text{current flowing in the line}}{\text{Current rating of the line}} \times 100 \quad (9)$$

4. Simulation and Results

The aforementioned section presented the developed power system AGC model and the associated dispatch strategy, which contemplate the transmission line overloading during the dispatch process to perform the daily generation and load balancing operation. The section implements the dispatch strategy and analyzes the results. To carry out this

objective, the study has modeled a hypothetical network of the Pakistan power system in which a specific part of the network is considered to implement and analyze the proposed control strategy. The selected part of the network is a 5-machine 8-bus model with 500 kV transmission lines connected through different buses and with different types of power plant units. The network consists of three THPPs units, GTPPs, and a WPP system. Generating units of THPPs, GTPPs, and WPPs are responsible for the primary reserves, while secondary reserves are delivered from the THPPs and WPPs following the proposed dispatch strategy. Furthermore, to investigate power changes on the external grid, the proposed power system network is coupled to an external grid that mimics the specific characteristics of a grid with a main frequency response of 6000 MW/Hz and an inertia of 16 s.

To understand the workings of the proposed power system AGC model, this study is divided into two phases. In the first phase, the effectiveness of the proposed dispatch strategy is analyzed for a step response of 150 MW when randomly applied on any bus of the power system network. In the second phase, the study implemented the same AGC model, utilizing a real-time input series for the generating units and connected loads. In both phases, the overloading of the transmission lines is analyzed during the dispatch process of the AGC model in the power balancing operation. Table 2 presents the current operating scenario, in which the power plant units are operating at different points to meet the daily load demand. Initially, before applying the step response, the load and the generation in the current scenario are balanced and, therefore, no imbalances in the power system are present, resulting in the frequency of the system being at the nominal level. The line loadings of the associated transmission lines are obtained in this scenario and are shown in Table 3. It is illustrated from the table that no line exceeded the limit of 90%, which is the maximum limit of line loading fixed in this study.

Table 2. Capacities, regulating reserves, and the initial operating points of generating units in a selected part of Pakistan’s power system network.

| Power Plant Models | THPP (Jamshoro) | THPP (Hubco) | THPP (Niki) | GTPP (Bhiki) | WPP (Jhampir) | Load (Jamshoro) | Load (Niki) | Load (Dadu) | Load (Guddo-New) |
|--------------------|-----------------|--------------|-------------|--------------|---------------|-----------------|-------------|-------------|------------------|
| Capacities | 1320 | 1202 | 800 | 220 | 2800 | – | – | – | – |
| Reserves | ±100 | ±100 | ±120 | 0 | –400 | – | – | – | – |
| I.O.P | 1188 | 1081.8 | 500 | 218 | 2520 | 2920.3 | 887.5 | 700 | 1000 |

Table 3. Ratings and current loading of the transmission lines in the balanced condition.

| Power System Trans-Lines | DU-GDN | DU-DGK | SKP-DU | DUN-SKP | JMS-DUN | HBC-JMS | HBC-NIKI |
|--------------------------|--------|--------|--------|---------|---------|---------|----------|
| Current ratings (KA) | 1.8 | 0.3 | 1.5 | 1.5 | 1.5 | 1.2 | 0.6 |
| Loadings (%) | 51.7 | 17.8 | 31.6 | 40.0 | 40.0 | 66.8 | 74.6 |

4.1. Step Response Analysis

To initiate the case study of the first phase, a load step of 150 MW was applied at the Niki bus station of the proposed power system network, deviating the system frequency from its nominal value, thus creating an imbalance between the load and generation. The system frequency is regulated by activating the secondary reserves following the primary reserves through the AGC system from the thermal power plants units ($\Delta P_{THPP(JMS)}$, $\Delta P_{THPP(HBC)}$, $\Delta P_{THPP(NIKI)}$) installed at different grid stations. The response of the AGC system is based on the calculated ACE signal (P_{ACE}) in the power system network, which is fed to the PI controller to determine the indispensable secondary response (ΔP_{Sec}) from the concerned power plant units. P_{ACE} and ΔP_{Sec} signals are resultantly drawn in Figure 6a to show the response of the area control error and the required power dispatch

to regulate the ACE signal. It is illustrated from the figure that the ΔP_{SEC} signal lag behind the P_{ACE} was due to the delays accompanying the AGC and the power plant units. The subsequent individual response ($\Delta P_{THPP(x)}$) of THPP units against the ACE signal is drawn in Figure 6b. For positive regulation, the required AGC response is divided among the different generating units of thermal power plants. However, for negative regulation, the wind power plant is also integrated into the AGC response along with thermal power plant units.

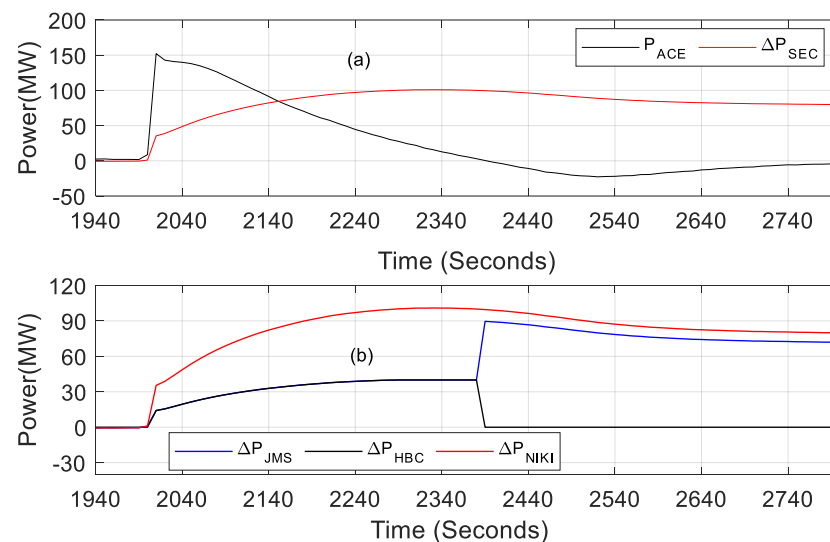


Figure 6. (a) ACE and the subsequent AGC response (b) Dispatch power from THPP units (Jamshoro, Hubco, and Niki).

From Figure 6, it can be seen clearly that when a load of 150 MW was applied at the Niki grid station, the AGC system automatically activated the reserve power from each generating unit taking part in the AGC dispatch process by keeping in view the line limit of each transmission line. In this process, all the lines approaching the Niki grid station would have a possibility to cross the threshold loading values to meet the increasing load demand at the Niki grid station. Hence, to alleviate the overloading of these lines, the dispatched power from all the buses connected to these lines should be reduced by the amount of overloaded power calculated with the help of Equation (9). In this case, the transmission line approaching the Niki grid station from the Hubco grid station became overloaded. This can be seen in Figure 6b between the time duration of 2340 and 2440 s, when the loading of a line connecting the Hubco and Niki grid station is overloaded as a result of the AGC operation and the response from the thermal power plant units is rescheduled to de-overload that specific line. The resulting dispatch power of the generating units shows that the generation at the Hubco grid station is reduced to zero, while the power from the generating unit of the Jamshoro grid station is reduced to a lower level. This is because the associated transmission lines of these grid stations are overloaded and, hence, a further dispatch from these generating units can overload these transmission lines. Conversely, the dispatched power by the generating unit at the Niki grid station (Local) is increased by the amount of power that the other two generating units have decreased in power. This does not affect the power balancing operation of the AGC system and, thus, the frequency of the system remains at the nominal level. Hence, the proposed dispatch strategy effectively regulated the area control error (P_{ACE}) by not violating the maximum line limit of the transmission lines, which is fixed at 90% in this study. This can be witnessed from the resultant response of the system frequency (Figure 7a) following the AGC response and subsequent response from the external grid, as shown in Figure 7b.

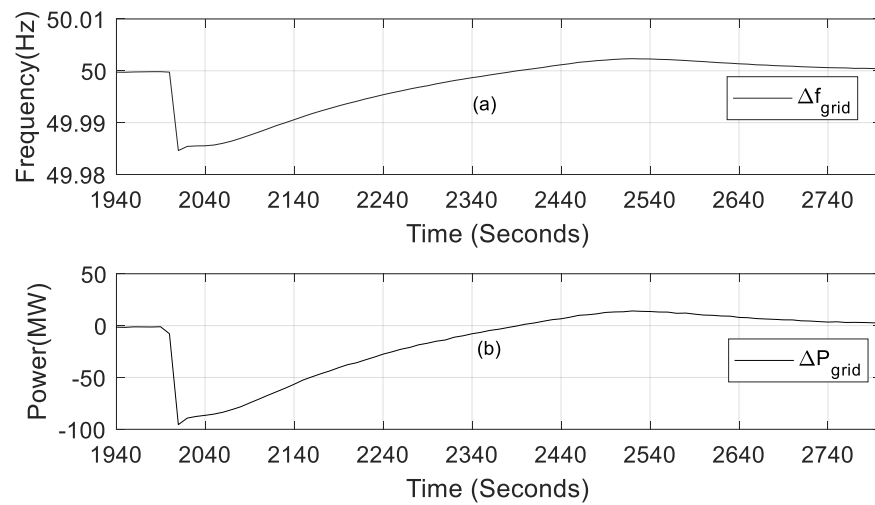


Figure 7. (a) Grid frequency and (b) Grid deviations following AGC response.

To further quantify the results, the steady-state values of the line loadings of all the transmission lines following the AGC response are presented in Table 4, and their responses are drawn in Figure 8, from which it can be illustrated that no line has crossed the limit of 90 %; hence, all the lines are operating within their nominal limits. Hence, the proposed AGC model effectively mitigated the imbalance engendered due to the load changes in the power system.

Table 4. Rating and current loading of the transmission lines following the AGC response.

| Power System Trans-Lines | DU-GDN | DU-DGK | SKP-DU | DUN-SKP | JMS-DUN | HBC-JMS | HBC-NIKI |
|--------------------------|--------|--------|--------|---------|---------|---------|----------|
| Current ratings (KA) | 1.8 | 0.3 | 1.5 | 1.5 | 1.5 | 1.2 | 0.6 |
| Loadings (%) | 51.7 | 17.8 | 31.6 | 39.9 | 39.9 | 60.0 | 88.2 |

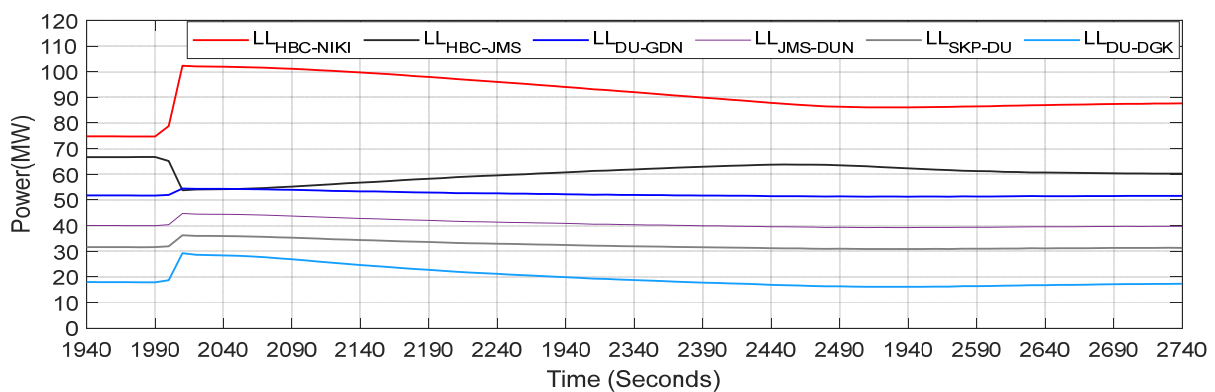


Figure 8. Line loading following AGC response.

Nevertheless, the line loadings remain within the limit, which ensures a secure and reliable operation of the power system. Furthermore, from Figure 8, it is illustrated clearly that the loading of the line connecting the HBC-NIKI grid station is reduced from the maximum limits between the time duration of 2340 and 2440 s. The resultant loading of the other lines following the AGC response is also shown in the figure, which shows that none of the lines crossed the maximum loading limits during the operation.

4.2. Real-Time Input-Based Analysis

The aforementioned section validated the proposed AGC dispatch strategy for avoiding the overloading of the transmission lines in the power balancing operation when a load step was applied at the Niki bus station. The developed dispatch strategy is further analyzed in this section utilizing a real-time input series for the generating units and connected loads. The capacities and the regulating reserves of the generating units and the connected loads are kept the same, as mentioned in Table 2. Furthermore, the initial generating power of all the power plant units is shown in Figure 9, in which three generating units are based on thermal power—one is a gas turbine and one is the wind power plant. Furthermore, the generating units based on the thermal power plant and the wind power plant contribute their power to the secondary regulation process. Here, it is important to mention that the forecast error in wind power engendered a power imbalance between the load and generation.

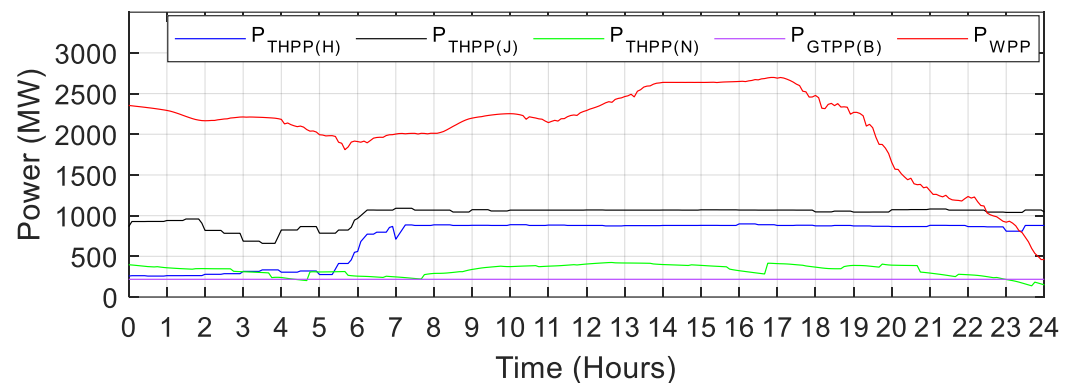


Figure 9. Initial generation from power plant units.

Figure 10 presents the initial power imbalance between the demand and generation resulting from the forecasting error of the wind power plant. The resulting imbalances are required to be mitigated by utilizing the secondary reserves from wind and thermal power plants installed at different buses. In this case, all the thermal power plants contribute to both positive and negative regulation, while the wind power plant only regulates negative power imbalances. Meanwhile, at the same time, the power flow of the transmission lines is measured by performing the load flow analysis according to the developed dispatch strategy. If any of the transmission lines cross the threshold value of the line loading as fixed by the operator, the dispatch ratio is optimized by the AGC regulator in a way that alleviates the overloaded lines by reducing the power generation from the concerned power plant units. The reduced power is equal to the amount required to de-alleviate the target-loaded lines. In addition, the deficient power is injected into the grid from the local grid station of the overloaded line. Conversely, if none of the lines cross the threshold load value, the dispatch ratio of the generating units would remain the same as it was before the loading impact. Here, the threshold value is set at 90% of the full line capacity.

Figure 11 illustrates the responses of all the generating units during the 24 h simulation period to provide the required reserve power during the AGC operation. Here, it can be seen from the figure that all the thermal power plants are actively participating in the positive and negative regulation process, while the wind power plant is only providing the regulation power during the negative regulation process. This is because the wind power plant is cheaper and always preferred to be operating at its maximum level. However, in this study, the generation capacity of wind power is reduced only if all the thermal power plants approach their lower operating level ($P_{chp, \min(x)}$), which is set to 20% of their full capacity, or the dispatched power of all the thermal power plants touches their lower limits. In such a situation, thermal power plants does not have sufficient reserves to be inculcated in the grid. Therefore, the wind power plant starts reducing its output power to regulate the P_{ACE} as per the requirement of the network.

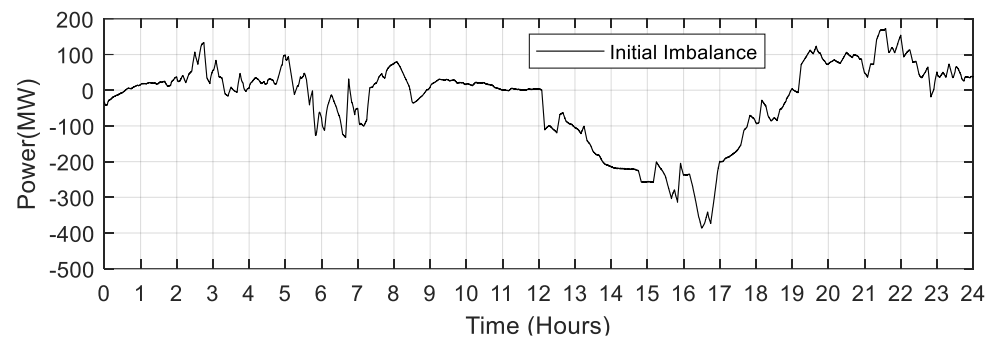


Figure 10. The initial power imbalance in the power system network.

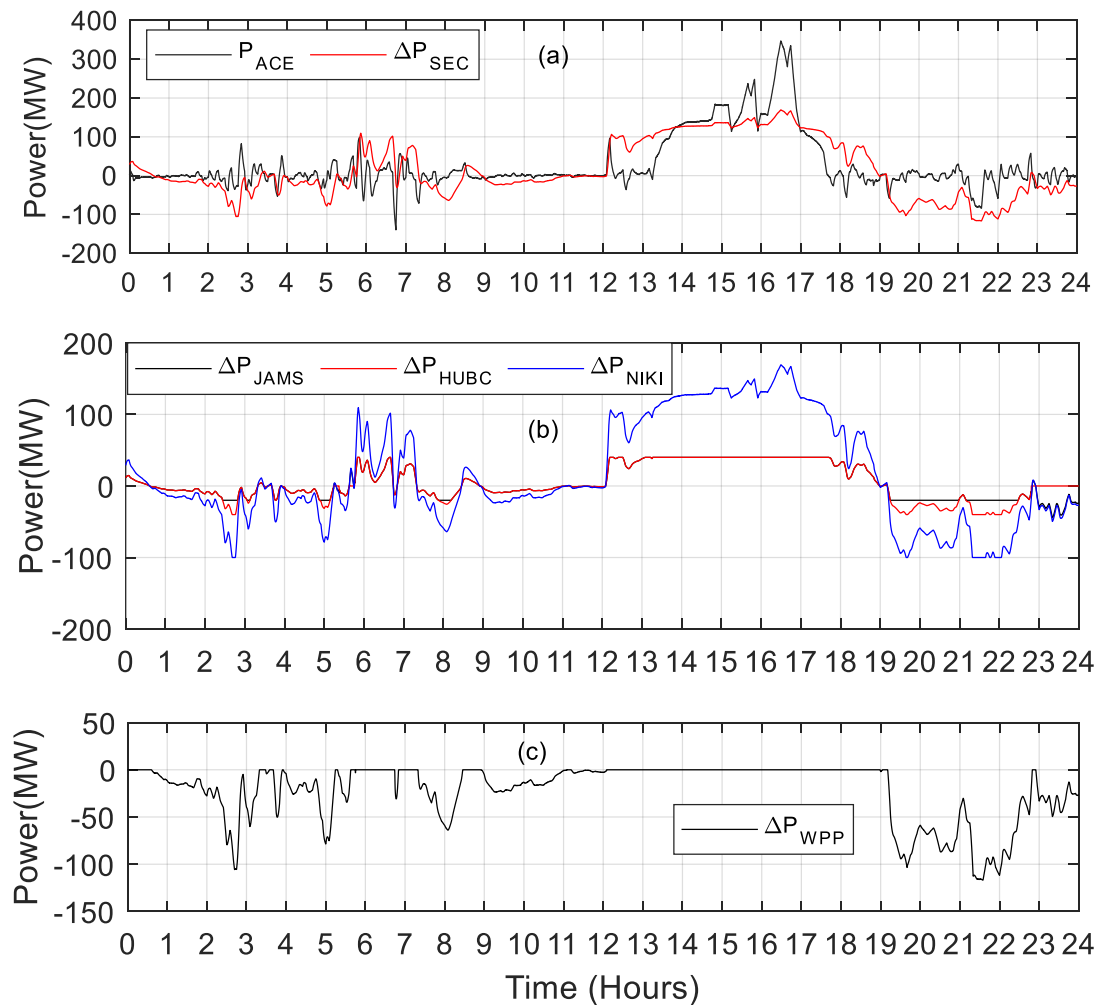


Figure 11. (a) ACE and the subsequent AGC response (b) Dispatch power from THPPs (Jamsh., Hubco & Niki), and (c) WPP (Jhimpir).

Along with such a regulation process, the dispatch mechanism takes into account the limitation of the transmission line capacities to avoid any overloading issues during the power balancing operation. To achieve this objective, regulating reserves are activated from those generating units, which do not overload the associated transmission lines. In this case, it can be seen from Figure 11 that the dispatched power is at a maximum from the Niki power plant and a minimum from the Jamshoro power plant units. Moreover, the reserve activation from the Hubco power plant system remained at the lowest level. This is because the line connecting the Hubco and Niki grid station is already operating at its maximum limit and further dispatches from the Hubco grid or any other grid station

may overload this line. However, the power from the local generating station at the Niki bus compensated for the required regulation power. The resultant response of all the lines in the network following the AGC operation is shown in Figure 12, where it can be seen that all the lines are operating below the maximum loading limit of 90%. Furthermore, it can be realized from the figure that the loading of the line connecting the Hubco to the Niki grid station remains at the maximum level and, therefore, the dispatch from the generating units installed at the associated buses remains at the lower level.

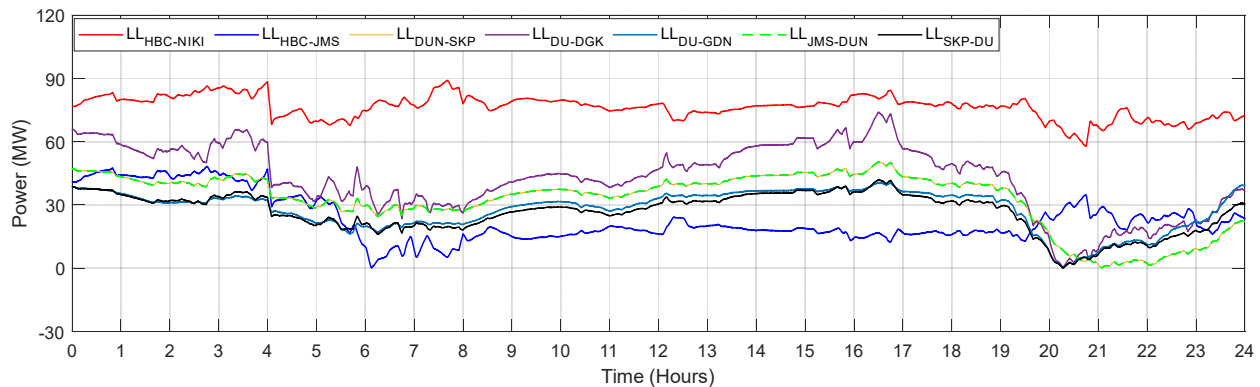


Figure 12. Line loadings following the AGC response.

Figure 13 presents the response of the grid frequency and the deviations of the AC interconnection. It is illustrated from the figure that the frequency of the system is regulated to its nominal level at different points during the simulation period. This is due to the activation of the reserve power from different generating units. The power deviations that appeared on the external grid are reduced by a substantial amount after the AGC response. Here, it is important to mention that the external grid deviations are the final imbalances, which will remain in the system following the AGC response.

The comparison of the initial and final power imbalance following the AGC response in the network is shown in Figure 14, from which it is illustrated that the initial power imbalance is reduced by a substantial amount after the activation of the reserve power from generation.

In addition, Figure 15 demonstrates the comparison of the loading power of the overloaded line during the AGC operation. From the figure, it can be concluded that the overloaded power has been significantly alleviated, bringing it to the level below the threshold value, which is fixed at 90% in this study. Hence, it can be concluded that the proposed dispatch strategy effectively performs the AGC operation and protects the transmission lines in the network.

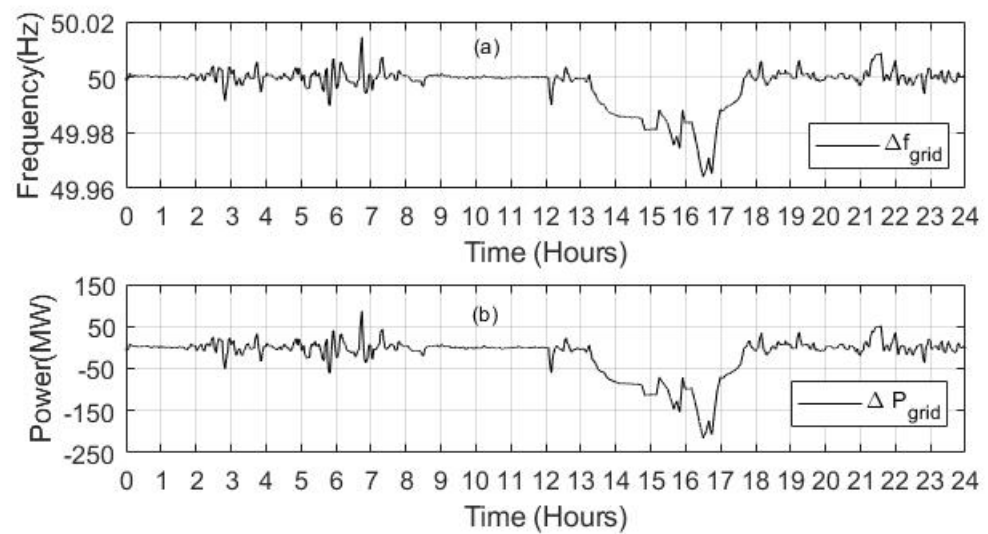


Figure 13. (a) Grid frequency and (b) Grid deviations following the AGC response.

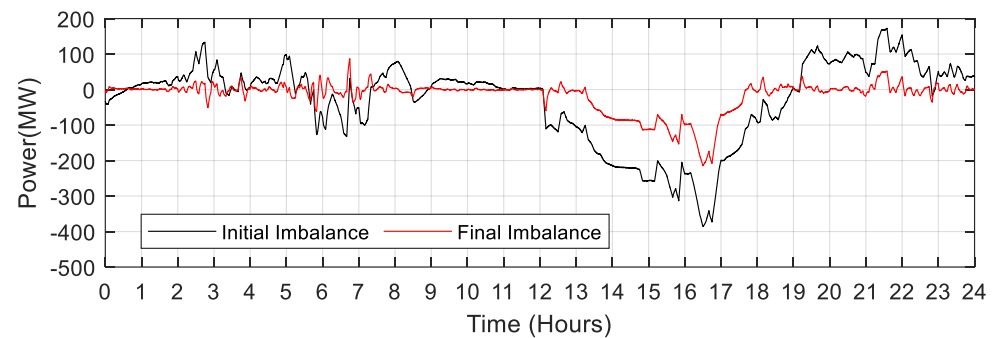


Figure 14. Comparison of initial and final power imbalances following the AGC operation.

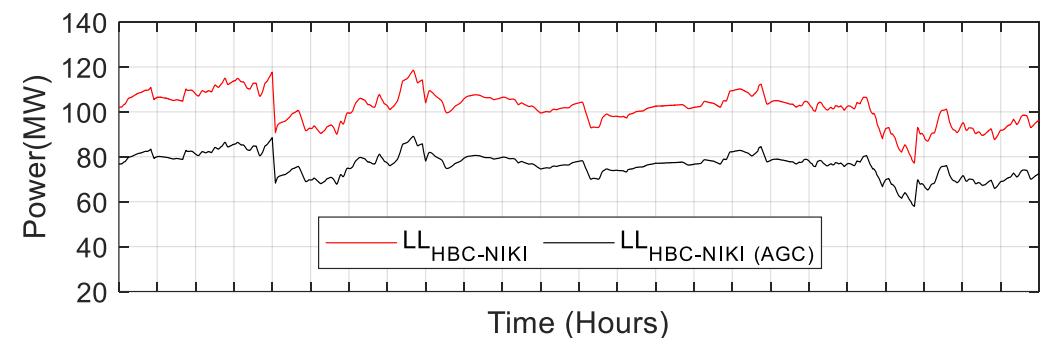


Figure 15. Comparison of the loading power of the overloaded line during AGC operation.

5. Conclusions and Future Directions

Concerns about the security and economy of the grids have increased due to developments in power system networks including the integration of large-scale wind energy sources, which engendered the power imbalance between the load and generation due to associated forecasting errors. Additional reserves are normally provided from the generating units to keep the balance in the network. However, the bulky injection of reserve power results in large fluctuations of the power flows in the associated transmission lines by not considering the transmission system constraints. This study incorporated the transmission line capacities in the real-time dispatch of the AGC system, resulting not only in an economic operation, but also avoiding transmission line overloading in real-time, thereby making the real-time operations secure and reliable. A simulation model consisting of a 5-machine 8-bus model was designed for the study in the Dig silent power factory software.

A real-time dispatch strategy was developed and implemented by performing the step response and the real-time input analysis. The results demonstrate that the suggested AGC design efficiently eliminates transmission line congestions during the daily load generation balancing operation while allowing generating units to operate economically.

In the present work, the proposed control strategy for avoiding line congestion was implemented in a single area network with minimum buses to minimize the computational burden. In the future, this work can be extended to the power system network, which has a multi-bus bar structure with interconnected power systems.

Author Contributions: Conceptualization, K.U., R.A. and S.A.; Data curation, A.B. and R.A.; Formal analysis, Z.U. and R.A.; Investigation, K.U., A.B., Z.U. and S.A.; Methodology, K.U., A.B. and Z.U.; Project administration, A.B., S.A. and A.Y.; Resources, A.Y.; Software, K.U., Z.U. and A.Y.; Validation, A.B., R.A. and S.A.; Visualization, R.A. and A.Y.; Writing – original draft, K.U., A.B. and Z.U.; Writing—review & editing, R.A., S.A. and A.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

| Acronym/Symbol | Definition |
|----------------------|--|
| GTPP | Gas turbine power plant |
| THPP | Thermal power plant |
| CLC | Command load signal |
| CIGRE | International Council on Large Electric Systems |
| FACTS | Flexible AC transmission system |
| PLB | Power limitation block |
| STC | Steam temperature control |
| φ_j [MW] | Active power flow in jth line |
| N_L, N_G | Number of loaded lines and generators |
| P_{LDi} [MW] | Load demand at ith bus |
| Y_{ij} | Mutual admittance |
| θ_{ij} | Line impedance angle |
| CVGV | Variable inlet guide vane position compressor capacity |
| GTDB | Gas turbine dynamics block |
| CSEV | Sequential environmental burner capacity |
| PDB | Power distribution block |
| CFM | Baseload function |
| DAG | Direct acyclic graph |
| GRC | Generation rate constraints |
| φ_{CP} [MW] | Maximum capacity of the line |
| P_{Gi} [MW] | Active power of the ith generator |
| N_B | Number of buses |
| δ_i, δ_j | Bus i and j voltage angles |
| ΔP_{Gi} [MW] | Dispatch power from an ith generator |

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