

Article

Optimization Strategy for Primary Frequency Regulation Coefficients Based on Grid Integration of New Energy Sources

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Abstract

The high penetration of wind power, photovoltaic, and energy storage not only presents opportunities for green and low-carbon development, but also poses significant challenges to frequency regulation. During primary frequency regulation (PFR), improper deadband settings may cause delayed or inadequate frequency responses, thereby exacerbating system frequency fluctuations, reducing renewable energy utilization rates, and compromising grid security and stability. This study proposes a parameter optimization method based on deadband to enhance PFR accuracy and improve overall energy conservation and emission reduction benefits. First, the impact of different deadband settings on system frequency fluctuations is analyzed, and the frequency response process is decomposed to quantify its effects on frequency stability and renewable energy integration capacity. Subsequently, the PFR coefficient is modified and optimized with maximum frequency deviation as the objective, thereby strengthening the frequency response capability of renewable energy. Simulation results demonstrate that the modified PFR coefficients reduce the maximum frequency deviation of wind–solar–storage systems by 0.0026 Hz, 0.0036 Hz, and 0.0034 Hz, respectively. This effectively elevates renewable energy integration levels and enhances the low-carbon stability of power system operations.

Keywords: renewable energy; primary frequency regulation; deadband; maximum frequency deviation; grid security and stability; frequency response

1. Introduction

With the rapid development and large-scale grid integration of new energy sources represented by wind power, photovoltaic technology, and energy storage, the operational characteristics and regulation requirements of power systems have undergone profound changes. Renewable energy sources exhibit intermittent, fluctuating, and unpredictable characteristics, significantly increasing the difficulty of grid frequency regulation. Improper frequency control not only exacerbates system frequency fluctuations and operational risks, but may also limit the utilization efficiency of renewable energy, thereby impacting energy conservation, emissions reduction, and the achievement of carbon peaking and carbon neutrality goals. Therefore, to enhance the responsiveness of renewable energy to frequency variations in the power system, the new power system requires renewable energy sources to possess the capability to participate in the primary frequency regulation (PFR) of the grid [1,2].

To address the challenges posed by the high penetration of renewable energy, power grids require more flexible and efficient frequency regulation capabilities. Among these,



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PFR serves as a critical component for maintaining system frequency stability, with its parameter settings directly determining the effectiveness of renewable energy units in frequency response. While conventional thermal power units have historically dominated frequency regulation, the continuous rise in renewable energy penetration makes reliance solely on traditional units insufficient to meet the system's demand for rapid frequency response. Therefore, there is an urgent need to research and optimize the PFR parameter settings for new energy sources to enhance their contribution to frequency control and new energy integration [3,4]. In-depth investigation into the impact of key parameters—such as the PFR coefficient for new energy—on grid frequency dynamics is crucial for improving system frequency regulation capabilities and ensuring the safe and stable operation of power systems [5].

Currently, extensive research has been conducted on the participation of wind power in the primary frequency regulation (PFR) of power systems. Existing studies mainly focus on enhancing frequency support capabilities using virtual inertia emulation, coordinated control, and advanced dispatch strategies. For instance, frequency regulation mechanisms of wind power plants—from inertial response to secondary control—have been systematically reviewed, and adaptive virtual inertia-based control strategies have been proposed to mitigate the degradation of system inertia and frequency stability under high wind-penetration conditions [6,7]. In parallel, robust dispatch and parameter optimization methods have been developed to improve wind power frequency support by considering uncertainty, available rotor kinetic energy, and adaptive control parameter adjustment [8,9]. Moreover, coordinated control strategies among multiple wind generators and between primary and secondary frequency responses have been explored to address inconsistent dynamic behaviors and oscillation issues in large-scale wind farms, including virtual elastic coupling control and virtual synchronous generator (VSG)-based coordination schemes [10,11]. In addition, enhanced frequency control methods for autonomous power systems with high wind power penetration have been investigated to alleviate the frequency stability problems caused by reduced system inertia [12].

With the increasing penetration of renewable energy sources, the coordinated participation of wind-storage and photovoltaic-storage systems in primary frequency regulation (PFR) has been widely investigated to enhance power system frequency stability. For wind-storage systems, various approaches have been proposed by combining virtual inertia control, droop control, improved torque limit control, and fuzzy prediction techniques to mitigate frequency nadir and secondary frequency drops under high wind-power penetration, while reducing energy storage capacity requirements and improving system frequency stability [13–16]. Similarly, for photovoltaic-storage systems, several coordinated control strategies have been developed based on virtual synchronous generator (VSG) technology, adaptive power regulation, and energy allocation optimization. These methods aim to improve frequency response speed, control accuracy, and system economic performance during PFR processes in high-renewable-penetration scenarios [17–20].

Despite these advances, most existing studies emphasize control structure design and operational coordination, whereas the determination of primary frequency regulation coefficients is often based on empirical tuning or fixed parameter settings without systematically considering renewable energy grid-integration characteristics and their coupling with power system frequency dynamics. Scholars have pointed out that the design of renewable energy frequency regulation strategies must account for the impact of deadband in frequency regulation [21–24]. However, no analysis has been conducted to improve the effectiveness of renewable energy frequency regulation by combining PFR coefficients with nonlinear deadband. To address this limitation, this paper proposes a systematic modeling and optimization framework for primary frequency regulation coefficients from

the perspective of renewable energy grid integration, thereby providing a more adaptive and robust frequency support solution for power systems with high renewable penetration.

Based on this, this paper proposes an optimization method for PFR parameters aimed at accommodating renewable energy and promoting energy conservation and emission reduction. By investigating the impact of different deadband settings on system frequency fluctuations and renewable energy response, combined with metrics such as maximum frequency deviation, the PFR coefficient is modified and optimized. This ensures system safety and stability while further enhancing renewable energy's participation in frequency regulation and its integration capacity. Simulation analysis using the IEEE 39-bus system as a case study verifies the reliability of the modified PFR coefficient. The findings not only contribute to promoting the stable operation of power systems under large-scale renewable energy integration, but also provide crucial technical support for achieving energy transition and the "carbon peaking and carbon neutrality" goals.

2. Establishment of Frequency Response Model Considering the PFR Deadband of Renewable Energy

When load disturbance occurs in the power system, in the whole dynamic frequency response process, the first stage is the new energy sources such as wind energy and photovoltaic energy using different control methods to participate in the inertia response process, respectively, to avoid a wide range of grid frequency drop. The second stage is the participation of energy storage in the wind turbine rotational speed restoration and photovoltaic capacitance voltage rebound process to avoid the frequency of the second drop and rapid fluctuation. Since the input time points of the frequency regulation resources are different, resulting in different time-domain expressions for the maximum frequency deviation and steady state frequency deviation, it is necessary to discuss the power deficit to satisfy the different operating states in separate cases. To enable analytical derivation and emphasize the impact of deadband nonlinearity on primary frequency response, this paper adopts a simplified aggregated model for wind power, photovoltaic units, and energy storage. Their PFR behaviors are represented by droop-like coefficients and capacity shares, while wind/PV are modeled with a conventional deadband and storage with a step-type deadband to reflect typical response characteristics. The model focuses on the PFR time scale (seconds to tens of seconds) and assumes that frequency deviations remain within normal operating limits. Converter inner-loop dynamics, detailed control interactions, and communication delays are not explicitly modeled. This framework is applicable for system-level frequency response assessment under high-renewable-energy penetration conditions.

As the power output of the wind turbine is limited by wind speed and the mechanical characteristics of the wind turbine, the response speed of wind power when it participates in the PFR of the grid is slow, and the power output of the wind turbine cannot immediately keep up with the demand for frequency changes. When the grid frequency fluctuation occurs, the wind turbine will not respond immediately, only when the frequency deviation exceeds a certain threshold, the wind power system will be regulated. As a result, the response curve of wind power tends to be flat and there exists a range of deadband called the normal-type deadband.

Photovoltaic systems rely heavily on real-time variations in solar energy, so their frequency regulation response has some lag and fluctuation. At smaller frequency deviations, the photovoltaic may not regulate immediately, but have a certain deadband. Especially in the case of small light changes, the photovoltaic system may not respond at low frequency changes until the frequency deviation exceeds a certain threshold. Therefore, the deadband is characterized as in the case of wind power.

Battery energy storage can complete charging and discharging within milliseconds to seconds, and is therefore capable of rapidly responding to changes in grid frequency. When grid frequency deviates, battery energy storage systems can rapidly adjust power output to participate in PFR. This implies the system exhibits a step-like response: it remains inactive until the frequency deviation reaches a specific threshold. Once the deviation exceeds this threshold, the battery storage immediately initiates regulation. This characteristic is termed a step-type deadband.

To facilitate analytical derivation and highlight the impact of deadband characteristics on primary frequency regulation performance, it is assumed that wind and solar power units possess a certain active power reserve capacity enabling participation in primary frequency regulation processes. Energy storage systems are assumed to have sufficient state of charge and rapid response capabilities, with their dynamic characteristics equivalent to a step-type deadband response. This paper primarily focuses on the short-term frequency dynamics of primary frequency regulation under small disturbance conditions. Under the aforementioned assumptions, the established model is applicable to power system scenarios with high penetration of renewable energy, where wind, solar, and energy storage systems possess primary frequency regulation capabilities, as shown in Figure 1.

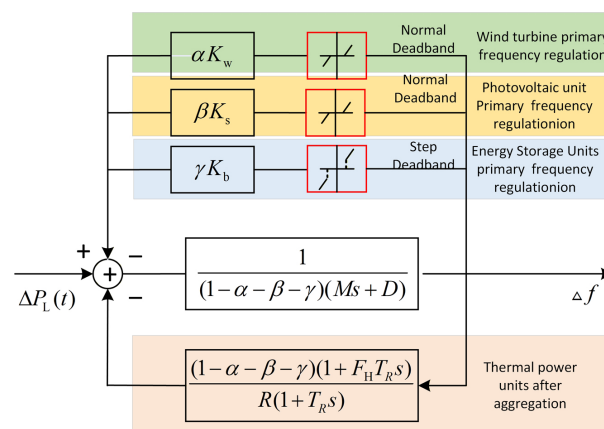


Figure 1. Frequency response modeling of a system with primary deadband for multiple types of energy sources.

In the figure, R is the static modulation coefficient of thermal power units; M is the inertia time constant; D is the damping coefficient; α , β , and γ represent the capacity shares of wind turbines, photovoltaic units, and battery energy storage respectively. $\Delta P_L(t)$ is the step disturbance power of the system; K_w , K_s , K_b are the PFR coefficients set when WTGs, PV units and battery storage are involved in frequency regulation respectively. F_H is the percentage of the high-pressure cylinder output to the total turbine output. T_R is the intermediate reheat steam volume time constant for thermal power units. The PFR output power $\Delta P_w(t)$ of the wind turbine can be calculated as

$$\Delta P_w(t) = -\alpha K_w f_w(t) \quad (1)$$

Similarly, the PFR output power of the PV unit and battery storage can be calculated as

$$\Delta P_s(t) = -\beta K_s f_s(t) \quad (2)$$

$$\Delta P_b(t) = -\gamma K_b f_b(t) \quad (3)$$

It can be concluded that the PFR output of conventional thermal power units can be calculated as

$$\Delta P_t(t) = -\Delta f(t) \frac{(1 - \alpha - \beta - \gamma)(1 + F_H T_{RS})}{R(1 + T_{RS})} \quad (4)$$

The deadband for PFR in the model refers to the range of frequency deviation from the rated value when the PFR function is inactive. Regulation only takes effect when the frequency change exceeds the rated frequency. When renewable energy sources participate in PFR of the grid, setting the deadband too narrow can cause frequent tripping of renewable units, leading to equipment damage and increased operational costs. Conversely, setting the deadband too wide prevents a timely response to significant grid frequency deviations, potentially causing frequency sags or overshoots and resulting in more severe frequency security issues. Therefore, establishing appropriate PFR deadband parameters is crucial for maintaining power system frequency stability.

For the modeled common type frequency regulation deadband, the relationship between frequency deviation and output is shown below [25]:

$$f(t) = \begin{cases} \Delta f(t) - d & \Delta f(t) > d, \\ 0 & |\Delta f(t)| \leq d, \\ \Delta f(t) + d & \Delta f(t) < -d, \end{cases} \quad (5)$$

For a step-type frequency regulation deadband, the relationship between the frequency deviation and output is shown below:

$$f(t) = \begin{cases} \Delta f(t) & |\Delta f(t)| \geq d, \\ 0 & |\Delta f(t)| < d, \end{cases} \quad (6)$$

In the formula, $\Delta f(t)$ denotes the frequency deviation, $f(t)$ represents the output after passing through the deadband circuit, and d indicates the frequency deadband threshold.

From the above equation, it can be seen that when the frequency crosses the deadband, the output of the standard type remains continuous; the output of the step-type undergoes a sudden step change.

In the multi-type energy PFR response system model, in addition to the deadband and PFR coefficients that have an impact on the PFR, the limiting amplitude also plays a role in the frequency regulation of the grid after the system is disturbed. Limit refers to when the grid is disturbed, the power system in a short period of time by adjusting the active power of the generator to respond to the frequency change, the new energy station in the participation of the PFR, and its power adjustment of the minimum amplitude requirements. The power change amplitude of the PFR of the new energy field station should meet the following requirements: when the system frequency is lower than the rated frequency, the new energy field station should increase the active power output according to the PFR curve, and the limit setting of the change amplitude of the PFR power should be not less than 6% of the operating power; when the system frequency is higher than the rated frequency, the new energy field station should reduce the active power output according to the PFR curve, and the change amplitude limit setting should be not less than 6% of the operating power. The change amplitude limit setting should be not less than 10% of the operating power [2].

However, the limiting amplitude does not affect the PFR effect of the new energy station alone, but works with the PFR coefficient to participate in the PFR of the power grid. In the frequency response calculation model with new energy PFR, the maximum

output power $\Delta P_{\max}$ of new energy participating in PFR and the corresponding frequency deviation Δf at this moment can be obtained, and the expression of new energy frequency regulation limit P_{limit} and PFR coefficient k can be further obtained by combining the critical deadband:

$$P_{\text{limit}} = \frac{\Delta P_{\max}}{P_N} \quad (7)$$

$$k = - \frac{\Delta P_{\max}}{\Delta f} \quad (8)$$

where P_N is the rated power capacity of the new energy field station.

From an engineering application perspective, the selection of limiting parameters and primary frequency regulation coefficients typically references common operational requirements and engineering experience for renewable energy participation in primary frequency regulation. This approach aims to achieve a reasonable balance among frequency support effectiveness, control intensity, and system stability. Consequently, the relationship between P_{limit} and k established in this paper reflects a widely adopted parameter configuration methodology, providing a sound theoretical basis for analyzing primary frequency regulation performance under varying operational conditions.

Based on the model in Figure 1 and the aforementioned formula, it can be seen that the PFR performance of new energy units is related to the deadband, limiting, and PFR coefficient. Since the deadband and limiting are manually set according to frequency fluctuations when new energy units participate in frequency regulation.

Further analysis of the aforementioned intrinsic causes reveals that for conventional frequency regulation, the fundamental factor significantly affecting frequency changes is the accuracy of feedback frequency deviation measurements. The response frequency exhibits a deviation of deadband d relative to the actual frequency. In contrast, step-type frequency regulation enable precise feedback of frequency deviation while featuring shorter system frequency trigger deadband times. This allows for new energy sources to rapidly participate in PFR, rendering step-type deadband virtually negligible in their impact on PFR effectiveness.

To bridge this gap and leverage the fast response capability of renewables, this paper proposes a PFR coefficient correction method. The core idea is to introduce a compensation gain c_0 ($c_0 > 1$) in the power command path of inverter-based resources (IBRs). This coefficient does not alter the physical deadband, but does correct the power reference signal to compensate for the initial energy shortfall inherent in the conventional response paradigm.

The coefficient c_0 acts as an energy compensation factor. It amplifies the initial power support from renewables, making their aggregate output equivalent to responding to a larger, “virtual” frequency deviation $\Delta f_{\text{virtual}} = c_0 \cdot \Delta f$. This effectively prepositions additional power injection during the frequency nadir formation, thereby elevating the frequency trough ($\Delta f_{\max}$) and improving both the maximum and steady-state frequency deviations.

The value of c_0 is typically determined using offline simulation studies to optimize the minimum frequency point under specific system conditions. However, its effectiveness is constrained by the following factors. For example, the penetration rate of new energy, system inertia, and disturbance magnitude all influence its ideal value. Therefore, the correction strategy depicted in Figure 2 intelligently compensates for the initial energy deficit, enabling renewable energy sources to provide virtual inertia and enhanced primary frequency response. This transforms their rapid response potential into superior system stability performance. As shown in Figure 2, f_{ref} where is the system reference frequency, f is the actual system frequency, and Δf is the system frequency deviation.

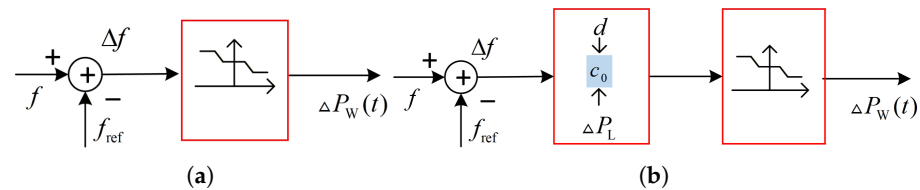


Figure 2. PFR strategy before and after optimization. They should be listed as follows: (a) PFR strategy before optimization (without the PFR coefficient factor). (b) PFR strategy after optimization (with the PFR coefficient factor).

3. Time-Domain Characterization of a Frequency Response Model with a New Energy PFR Deadband

Due to the nonlinear characteristics of the deadband mentioned in the previous section, it can be divided into different stages in the dynamic frequency regulation process, and the deadband segments are linearly derivable, so that the nonlinear model can be decomposed into a number of different stages of the linear model. The continuity before and after the demarcation point and the input time of different new energy sources are guaranteed to solve the frequency dynamic time-domain differential equations.

According to Figure 1, the output of the deadband $f(t)$ is decomposed into state variables $x_w(t)$, $x_s(t)$ and $x_b(t)$, and the time-domain differential equations for the state variables and $\Delta f(t)$ are established in the following equation:

$$MT_R \Delta \ddot{f}(t) + (M + DT_R + \frac{F_H T_R}{R}) \Delta \dot{f}(t) + \frac{\mu k T_R}{1 - \mu} \dot{x}(t) + (D + \frac{1}{R}) \Delta f(t) + \frac{\mu k}{1 - \mu} x(t) = \frac{\Delta P_L(t) + T_R \Delta \dot{P}_L(t)}{1 - \mu} \quad (9)$$

where $\Delta \dot{P}_L(t)$ is the first-order derivative of the step power perturbation with respect to time and is also the impulse function. The total share of renewable energy is expressed as $\mu = \alpha + \beta + \gamma$. The PFR coefficient of renewable energy is $k = K_w + K_s + K_b$, and the state variable of the deadband output is given by $x(t) = x_w(t) + x_s(t) + x_b(t)$.

Since the differential equation of the frequency regulation deadband contains the step function and its derivative impulse function term, which will cause the state quantity to change abruptly, resulting in the system dynamic time-domain differential equation not being able to be analyzed. Therefore, this paper adopts the segmentation in and out of the deadband to solve the dynamic time-domain analytical equation of the system frequency. The time-domain differential equation is rearranged as shown in Equation (10).

$$\Delta \ddot{f}(t) + \frac{MR + DRT_R + F_H T_R}{MT_R R} \Delta \dot{f}(t) + \frac{1 + DR}{MT_R R} \Delta f(t) + \frac{\mu k T_R}{1 - \mu} \dot{x}(t) + \frac{\mu k}{1 - \mu} x(t) = \frac{\Delta P_L(t) + T_R \Delta \dot{P}_L(t)}{1 - \mu} \quad (10)$$

Due to the discontinuous state of the system, the different time of wind energy storage input action, and the different output, it is necessary to analyze the effect of wind energy storage frequency regulation on the frequency dynamics at different stages.

Solving the above time-domain differential equation yields the generalized form of $\Delta f(t)$ as follows:

$$\begin{cases} \Delta f(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + \Delta f^* \\ \Delta f^* = \frac{R \Delta P_L}{(1 - \mu)(1 + DR)} \end{cases} \quad (11)$$

Among them, $C_1 = \frac{\Delta P_L(MR\lambda_2 + DR + 1)}{M(1-\mu)(\lambda_1 - \lambda_2)(1 + DR)}$, $C_2 = \frac{\Delta P_L(MR\lambda_1 + DR + 1)}{M(1-\mu)(\lambda_2 - \lambda_1)(1 + DR)}$, λ_1 , λ_2 are the characteristic roots of the equation. It should be noted that the introduction of the frequency regulation deadband leads to a piecewise dynamic behavior, as the system's differential equations involve step functions and their derivatives, which introduce impulse terms at the deadband boundaries. To address this issue, the system dynamics are modeled separately inside and outside the deadband, where each segment can be treated as a linear time-invariant system, enabling analytical solutions of the frequency dynamics. By imposing state continuity conditions at the instant immediately after the disturbance ($t = 0^+$) and determining the initial conditions based on the impulse balance principle, the continuity of frequency deviation across deadband segmentation boundaries is ensured, allowing for a consistent time-domain analytical analysis of the frequency response.

Within the PFR deadband of renewable energy sources, only synchronous machines participate in system frequency regulation, as renewables have not yet engaged in frequency response. Therefore, the time-domain solution for the frequency dynamic deviation in the frequency regulation deadband is

$$\Delta f(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + \frac{R \Delta P_L}{(1 - \mu)(1 + DR)} \quad (12)$$

3.1. Common Type Frequency Regulation Deadband Outside Solving

However, when system frequency shifts beyond the renewable energy deadband, the model depicted in Figure 1 indicates that the frequency regulation deadband for renewables is categorized into common and step-type.

When the system frequency falls to the deadband at t_0 time, $\Delta \dot{P}_L(t) = 0$, substituting Equation (5) into Equation (9), the dynamic frequency differential equation of the system is obtained as follows:

$$\begin{aligned} \Delta \ddot{f}(t) + \frac{(1 - \mu)(MR + DRT_R + F_H T_R) + \mu k T_R R}{MT_R R(1 - \mu)} \Delta \dot{f}(t) \\ + \frac{(1 - \mu)(1 + DR) + \mu k R}{MT_R R(1 - \mu)} \Delta f(t) = \frac{\Delta P_L(t)}{MT_R(1 - \mu)} \end{aligned} \quad (13)$$

Solving for $\Delta f(t)$ outside the deadband leads to the following generalized form:

$$\begin{cases} \Delta f(t) = C_3 e^{\lambda_3(t-t_0)} + C_4 e^{\lambda_4(t-t_0)} + \Delta f_0 \\ \Delta f_0 = \frac{R \Delta P_L - R \mu k d}{(1 - \mu)(1 + DR) + \mu k R} \end{cases} \quad (14)$$

where C_3 , C_4 are constants, λ_3 , λ_4 are the characteristic roots of Equation (14), t_0 is the moment when the frequency falls to the deadband, and Δf_0 is the special solution of Equation (13).

Therefore, consider the new energy using the frequency deviation time-domain solution outside the normal type deadband as follows:

$$\Delta f_0(t) = \begin{cases} C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + \frac{R \Delta P_L}{(1 - \mu)(1 + DR)} & 0 < t \leq t_0, \\ C_3 e^{\lambda_3(t-t_0)} + C_4 e^{\lambda_4(t-t_0)} + \frac{R \Delta P_L - R \mu k d}{(1 - \mu)(1 + DR) + \mu k R} & t > t_0. \end{cases} \quad (15)$$

3.2. Step-Type Frequency Regulation Deadband Outside Solving

When the frequency deviation crosses the deadband, substituting Equation (6) into Equation (9) yields the system frequency differential equation as follows:

$$\Delta \ddot{f}(t) + \frac{(1-\mu)(MR + DR_R + F_H T_R) + \mu k T_R R}{MT_R R(1-\mu)} \Delta \dot{f}(t) + \frac{(1-\mu)(1 + DR) + \mu k R}{MT_R R(1-\mu)} \Delta f(t) = \frac{\Delta P_L(t)}{MT_R(1-\mu)} \quad (16)$$

Solving for $\Delta f(t)$ outside the deadband leads to the following generalized form:

$$\begin{cases} \Delta f(t) = C_5 e^{\lambda_3(t-t_0)} + C_6 e^{\lambda_4(t-t_0)} + \Delta f_s \\ \Delta f_s = \frac{R \Delta P_L}{(1-\mu)(1 + DR) + \mu k R} \end{cases} \quad (17)$$

where C_5, C_6 are constants, λ_3, λ_4 are characteristic roots of Equation (17), t_0 is the moment when the frequency falls to the deadband, and Δf_s is the special solution of Equation (16).

Therefore, consider the new energy using the frequency deviation time-domain solution outside the step-type deadband as follows:

$$\Delta f_s(t) = \begin{cases} C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + \frac{R \Delta P_L}{(1-\mu)(1 + DR)} & 0 < t \leq t_0, \\ C_5 e^{\lambda_3(t-t_0)} + C_6 e^{\lambda_4(t-t_0)} + \frac{R \Delta P_L}{(1-\mu)(1 + DR) + \mu k R} & t > t_0. \end{cases} \quad (18)$$

By analyzing the characteristics of frequency regulation deadband segment linearization and the boundary conditions before and after the deadband, the frequency dynamic response process under the consideration of the influence of the new energy PFR deadband is successfully solved under the premise of ensuring the system frequency stability.

4. Analysis of the Effect of New Energy PFR Dynamic Parameters on Frequency Deviation

Next, this paper will further analyze in depth the specific impact of the deadband nonlinear characteristic on the frequency safety of the system based on the obtained frequency dynamic time-domain solution. This analysis will provide a theoretical basis for the optimization of the new energy PFR parameters, and the frequency regulation parameters will be corrected accordingly to improve the frequency stability and safety of the system.

When the system is perturbed, a frequency minimum exists during PFR and gradually oscillates to the steady-state value. The maximum frequency deviation and the steady-state frequency deviation are two key metrics that indicate the frequency safety of the system. In this section, the analytical time-domain expression for the frequency dynamics based on considering the new energy frequency regulation deadband is solved.

Due to the different input times of wind and solar storage, it is necessary to segment the time-domain solution expression for frequency deviation to solve for the maximum frequency deviation and steady state frequency deviation.

When the normal-type frequency falls to the lowest point, the first-order derivative of the frequency deviation is zero, i.e., $\Delta \dot{f}(t) = 0$. The corresponding moment $t_{1,\max}$ of the lowest point of the frequency can be found to be

$$t_{1,\max} = \frac{\ln(-C_4\lambda_4) - \ln(-C_3\lambda_3)}{\lambda_3 - \lambda_4} + t_0 \quad (19)$$

When the step-type frequency falls to its lowest point, the corresponding moment $t_{2,\max}$ is

$$t_{2,\max} = \frac{\ln(-C_6\lambda_4) - \ln(-C_5\lambda_3)}{\lambda_3 - \lambda_4} + t_0 \quad (20)$$

Substituting Equations (17) and (18) into Equations (13) and (16), respectively, the maximum frequency deviation and steady-state frequency deviation expressions considering the new energy frequency regulation deadband are obtained as

$$\begin{cases} \Delta f_{1,\max} = C_3 e^{\lambda_3 t_{\max}} + C_4 e^{\lambda_4 t_{\max}} + \frac{R\Delta P_L - R\mu kd}{(1-\mu)(1+DR) + \mu kR} \\ \Delta f_{2,\max} = C_5 e^{\lambda_3 t_{\max}} + C_6 e^{\lambda_4 t_{\max}} + \frac{R\Delta P_L}{(1-\mu)(1+DR) + \mu kR} \end{cases} \quad (21)$$

$$\begin{cases} \Delta f_{1,\infty} = \frac{R\Delta P_L - R\mu kd}{(1-\mu)(1+DR) + \mu kR} \\ \Delta f_{2,\infty} = \frac{R\Delta P_L}{(1-\mu)(1+DR) + \mu kR} \end{cases} \quad (22)$$

where $\Delta f_{1,\max}$ and $\Delta f_{2,\max}$ are the maximum frequency deviations of the system when the new energy adopts normal deadband and step-type deadband, respectively. Similarly, $\Delta f_{1,\infty}$ and $\Delta f_{2,\infty}$ are the steady-state frequency deviations of the system when the new energy adopts normal deadband and step-type deadband, respectively.

From the above equation, it can be seen that the frequency deviation of the power grid is related to parameters such as the new energy PFR coefficient k , frequency regulation deadband d , and so on. Therefore, it is necessary to manually set an appropriate PFR coefficient to improve the power system's frequency regulation capability. When the new energy frequency regulation system adopts different artificially set deadbands, the moment of its frequency regulation action and the depth of frequency regulation are different; reducing the new energy frequency regulation deadband can effectively reduce the frequency fluctuations in the power grid. Assign typical values to the governor parameters as follows: $R = 0.05$, $M = 10$, $D = 1$, $T_R = 10$, $F_H = 0.3$, $\alpha = 0.1$, $\beta = 0.1$, and $\gamma = 0.1$. To analyze the effect of new energy PFR parameters on the system frequency deviation, a 20% load surge perturbation is imposed using the parameters in Figure 1, with the PFR deadband varied from 0.02 to 0.1 Hz and the PFR coefficient varied from 10 to 50 [26]. The frequency deviation of the system then varies with the frequency regulation parameter indicators as follows.

From Figure 3, it can be seen that, for the normal frequency regulation, the deadband and the PFR coefficient have an effect on the maximum frequency deviation as well as the steady-state frequency deviation, and they are positively correlated, i.e., the larger the frequency regulation deadband setting, the larger the corresponding maximum frequency deviation and steady-state frequency deviation. For the step-type frequency regulation, the deadband has almost no effect on the maximum frequency deviation and steady state frequency deviation. The PFR coefficient, on the other hand, has an effect on both the maximum frequency deviation and the steady-state frequency deviation, which are negatively correlated.

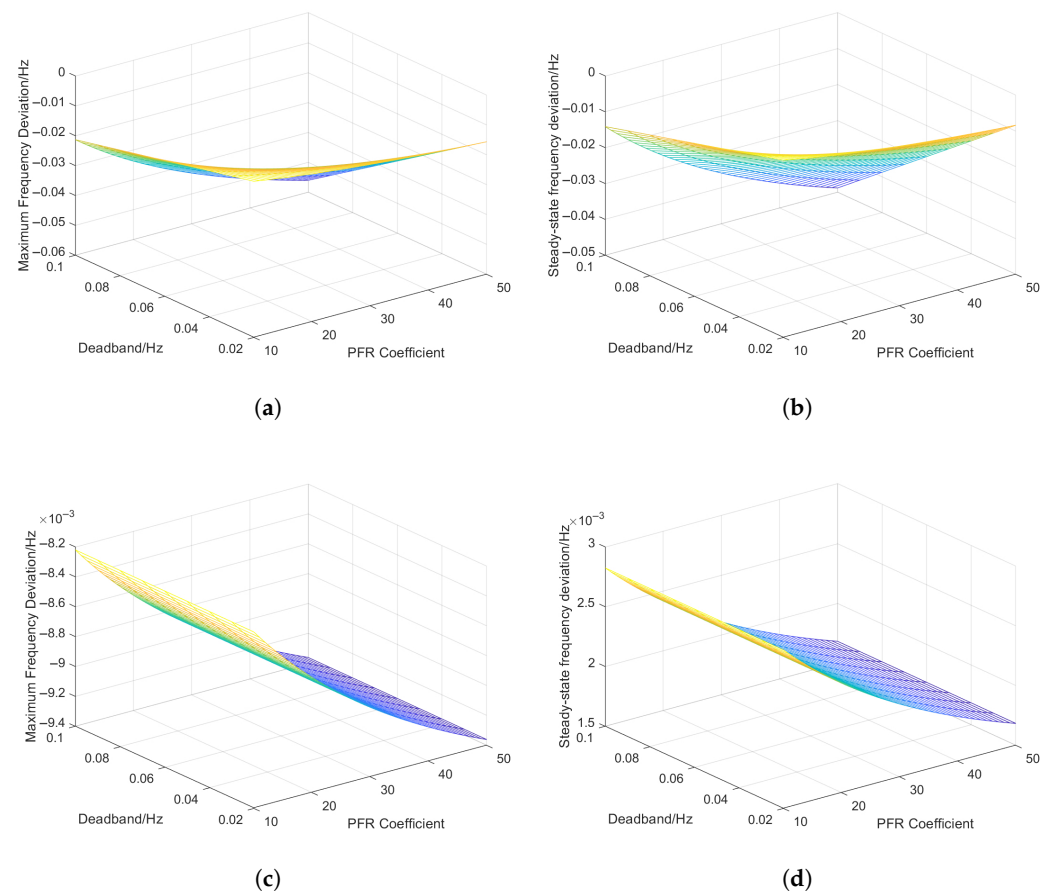


Figure 3. The impact of PFR parameters of new energy on frequency deviation. They should be listed as follows: (a) Maximum frequency deviation for normal type. (b) Steady-state frequency deviation for normal type. (c) Maximum frequency deviation for step type. (d) Steady-state frequency deviation for step type.

In summary, in this section, based on the system frequency response analytical equation, the effect of the new energy PFR deadband is considered, and the effect of the new energy PFR parameters on the frequency deviation is analyzed. It is shown that the deadband in the ordinary type weakens the expected PFR effect of the new energy, while the deadband d in the step-type has less effect on the frequency regulation effect of the system. The PFR coefficients k of both normal and step types have an effect on both the maximum frequency deviation and the steady-state frequency deviation. Based on the above conclusions, a strategy for the correction of the new energy PFR coefficients considering the two types of frequency regulation deadband is subsequently proposed.

5. Nonlinear Effects of Deadband Based on Frequency-Resolved Solutions and PFR Coefficient Correction Strategy

Under a conventional PFR deadband, renewable energy units respond based on a reference frequency lower than the actual frequency deviation. When the frequency regulation capacity is sufficient, this mechanism weakens the PFR capability of renewable energy sources, leading to wasted regulation resources and increasing the burden on synchronous machines. To address this, a strategy for modifying the PFR coefficient of renewable energy sources is proposed.

For the new energy PFR deadband, the PFR coefficients can be corrected to improve the new energy PFR response level, so the parameters in Figure 2 are assigned values

considering the deadband: $M = 4$, $D = 0.05$, $R = 0.05$, $T_R = 10$, $F_H = 0.3$. The total capacity of new energy accounts for the frequency regulation response time constant, 0.5; a 20% load surge perturbation is applied at 1 s, and the frequency regulation end time is 20 s. With a new energy penetration rate of 30%, the dynamic frequency regulation parameters of wind power, photovoltaic and energy storage refer to the “Guide for technology and test on primary frequency control of grid-connected power resource”, as shown in Tables 1–3.

Table 1. New energy dynamic frequency regulation parameter configuration case 1.

Parameters	Deadband	Power Limiting	PFR Factor
Wind	0.1	10%	33
PV	0.06	10%	33
ESS	0.05	10%	33

Table 2. New energy dynamic frequency regulation parameter configuration case 2.

Parameters	Deadband	Power Limiting	PFR Factor
Wind	0.03	10%	33
PV	0.02	10%	33
ESS	0.03	10%	33

According to the simulation results in Figure 4, it can be seen that the PFR deadband of new energy wind power, photovoltaic technology, and energy storage are reduced by 0.07 Hz, 0.04 Hz, and 0.02 Hz, respectively, and the maximum frequency deviation of the system is reduced by 0.0125 Hz, which is in line with the conclusion that the PFR deadband of new energy are positively related to the maximum frequency deviation of the system.

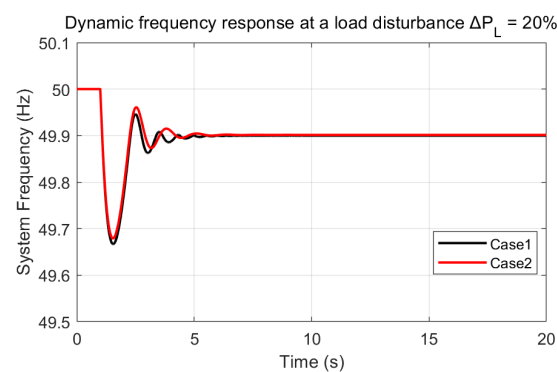


Figure 4. Dynamic frequency response of new energy under different deadband.

On the basis of the above unchanged frequency regulation parameters, the impact of changing the PFR coefficients on the dynamic characteristics of the grid frequency is analyzed, as shown in Table 3.

Table 3. New energy dynamic frequency regulation parameter configuration case 3.

Parameters	Deadband	Power Limiting	PFR Factor
Wind	0.1	10%	50
PV	0.06	10%	50
ESS	0.05	10%	50

According to the simulation results in Figure 5, it can be seen that in the wind power, photovoltaic technology, and energy storage, the deadband and limit amplitude must

be, the PFR coefficient increased from 33 to 50, respectively, and the system's maximum frequency deviation and steady-state frequency deviation decreased by 0.0147 Hz and 0.0024 Hz, respectively, which is consistent with the conclusion that the new energy's PFR coefficient and the system's maximum frequency deviation and steady-state frequency deviation are negatively correlated.

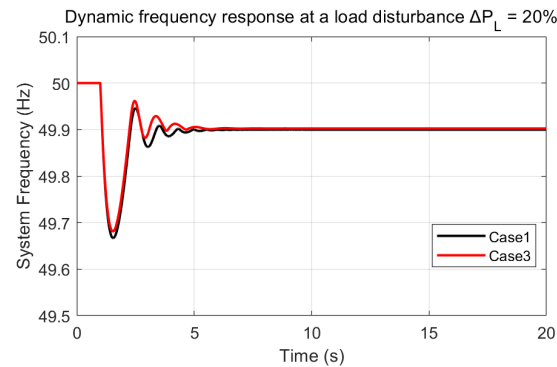


Figure 5. Dynamic frequency response of new energy under different frequency regulation coefficients.

Taking the maximum frequency deviation as a reference, the correction coefficients of Equation (20) are calculated and the ability of the correction coefficients to enhance the frequency minimum is examined.

Since the effect of reducing the maximum frequency deviation is more significant, a reasonable target value for the maximum frequency deviation $\Delta f(t)_{\max, \text{target}}$, which is the minimum point deviation of the frequency that the system is expected to achieve, is set as follows:

$$\Delta f(t)_{\max, \text{target}} = C_5 e^{\lambda_3 t_{2, \max}} + C_6 e^{\lambda_4 t_{2, \max}} + \frac{R \Delta P_L}{(1 - \mu)(1 + DR) + \mu k R} \quad (23)$$

To make the maximum frequency deviation of the system satisfy the desired target, a correction coefficient c_0 can be introduced to make the new energy PFR coefficient become $c_0 k$, as shown in Figure 4. Compare the maximum frequency deviation $\Delta f(t)_{\max}$ of the actual system with the target value $\Delta f(t)_{\max, \text{target}}$ to solve the expression of c_0 :

$$c_0 = \frac{\Delta f(t)_{\max, \text{target}} - C_3 e^{\lambda_3 t_{1, \max}} - C_4 e^{\lambda_4 t_{1, \max}}}{\Delta f(t)_{\max} - C_3 e^{\lambda_3 t_{1, \max}} - C_4 e^{\lambda_4 t_{1, \max}}} \quad (24)$$

This paper proposes four limiting schemes for new energy units, as shown in Table 4.

Table 4. Analysis of the synergistic impact of limits on various types of units.

Categorization	Power Limiting (PV)	Power Limiting (Wind)	Power Limiting (ESS)	PFR Factor
Case 4	PV 6%	Wind 6%	ESS 10%	33
Case 5	PV 6%	Wind 8%	ESS 10%	33
Case 6	PV 7%	Wind 8%	ESS 10%	33
Case 7	PV 8%	Wind 8%	ESS 10%	33

According to the simulation results in Figure 6, the following can be seen: in the case of the new energy PFR coefficient remaining unchanged, the limit determines the maximum power that the new energy unit can provide in the frequency regulation process; the larger the limit is, the more frequency regulation power the unit can provide; and the smaller the frequency dropout, the stronger the unit's total frequency regulation capability, and the smaller the steady state frequency deviation. The opposite is also true.

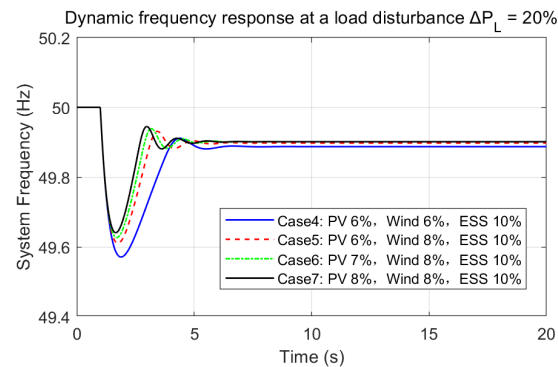


Figure 6. Dynamic frequency response of new energy sources with four different limits.

In practical applications, the new energy involved in the PFR limit and the PFR coefficient need to be set in concert. The PFR coefficient cannot be infinitely too large; if the PFR coefficient is too high, the system's response is fast and the frequency deviation is small, which may cause oscillation; if the PFR coefficient is too low, the system's response is slower, but the system is more stable. The relationship between the limiting amplitude and the PFR factor is shown in Equation (25), and the PFR factors of different new energy units need to be allocated proportionally according to the capacity to avoid overloading of a single unit [27].

$$k \leq \frac{P_{\text{limit}} \times 100\%}{\Delta f_{\text{max}}} \quad (25)$$

In the formula, P_{limit} represents the percentage of disturbance load, k denotes the PFR coefficient of new energy sources, and Δf_{max} indicates the maximum frequency deviation.

From Figure 4, it can be seen that the maximum frequency deviation before the correction in this section is 0.3335 Hz, and the load disturbance P_{limit} is 20%, so k should be ≤ 59.97 both before and after the correction.

According to the obtained c_0 , the frequency nadir is increased by 0.067 Hz, and the new energy frequency regulation coefficient is corrected to $c_0 k$.

From Equation (25) and Table 5, it can be concluded that the corrected PFR coefficient is 35.97 when the deadband, limiting amplitude, and disturbance are unchanged. According to the simulation results in Figure 7, the maximum frequency deviation is reduced by 0.0057 Hz after the correction of the PFR coefficient, and the steady-state frequency deviation is reduced by 0.0079 Hz, which also satisfies the conclusion that the frequency deviation of the system is negatively correlated with the frequency regulation coefficient. And the corrected frequency regulation coefficient ensures that the maximum frequency deviation is reduced while the steady state frequency deviation is also reduced.

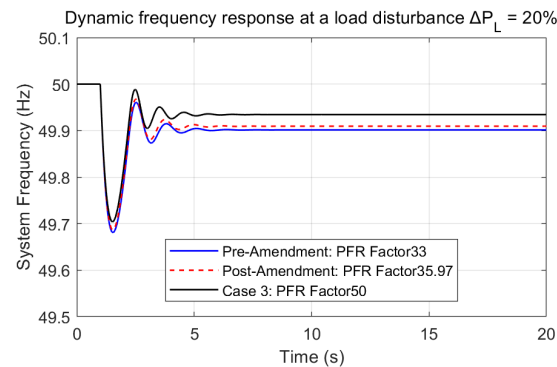
Table 5. Simulation results for each type of unit.

Categorization	Maximum Frequency Deviation	Steady-State Frequency
Case 4	0.4291 Hz	49.8873 Hz
Case 5	0.3898 Hz	49.8978 Hz
Case 6	0.3734 Hz	49.9015 Hz
Case 7	0.3594 Hz	49.9015 Hz

The modified frequency modulation coefficient according to Equation (24) is shown in Table 6.

Table 6. Analysis of the effect of corrected frequency regulation coefficients on frequency deviation.

Parameters	Deadband	PFR Factor	Modified Coefficient	Maximum Frequency Difference Change
Wind	0.1	33	35.97	0.0057
PV	0.06	33	35.97	0.0057
ESS	0.05	33	35.97	0.0057

**Figure 7.** Corrected new energy dynamic frequency response at one frequency regulation factor.

The premise of the comparison of the above frequency regulation schemes is that the new energy penetration rate is 30%. Considering that the correction of the PFR coefficient is related to the penetration rate, the comparison of the frequency regulation parameters and the frequency regulation effect of the different units with new energy penetration rate of 50% and 70% are shown in Tables 7–9 and Figures 8–10.

Table 7. Frequency regulation parameters of new energy units at 30% penetration rate.

Parameters	Deadband	Power Limiting	PFR Factor	Modified Coefficient
Wind	0.02	8%	20	21.8
PV	0.03	8%	20	21.8
ESS	0.03	10%	33	35.97

Table 8. Frequency regulation parameters of new energy units at 50% penetration rate.

Parameters	Deadband	Power Limiting	PFR Factor	Modified Coefficient
Wind	0.02	8%	20	23.6
PV	0.03	8%	20	23.6
ESS	0.03	10%	33	38.94

Table 9. Frequency regulation parameters of new energy units at 70% penetration rate.

Parameters	Deadband	Power Limiting	PFR Factor	Modified Coefficient
Wind	0.02	8%	20	25.4
PV	0.03	8%	20	25.4
ESS	0.03	10%	33	41.91

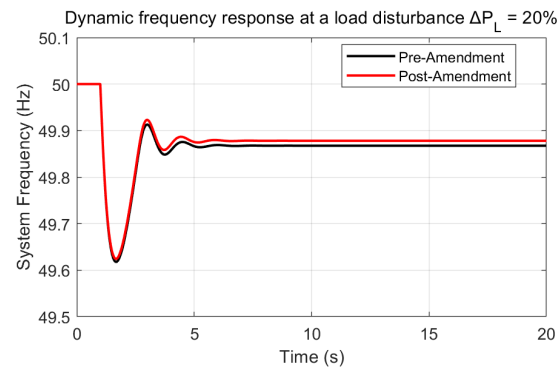


Figure 8. Plot of frequency regulation waveform observations before and after correction of 30% penetration PFR.

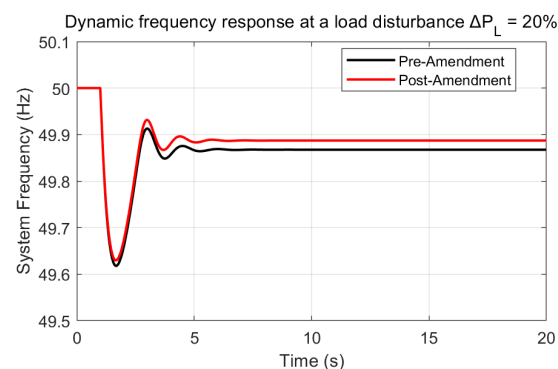


Figure 9. Plot of frequency regulation waveform observations before and after correction of 50% penetration PFR.

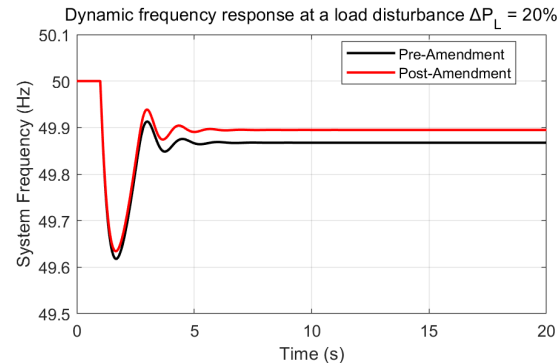


Figure 10. Plot of frequency regulation waveform observations before and after correction of 70% penetration PFR.

6. Case Studies

In order to verify the effect of the PFR coefficient correction on the frequency characteristics of the system, this paper uses the IEEE39 node arithmetic in the PSASP power system simulation program platform for simulation analysis, and the system wiring diagram is shown in Figure 11.

The model includes ten generators, 39 nodes, the initial frequency of the system is 50 Hz, the capacity of the thermal power unit is 40 MW, the thermal power unit modulation coefficient is set to 0.05, the inertia time constant of the system is 10 s, and the damping constant of the system is 2. The new energy field station consists of 45 MW doubly fed wind turbines, 20 MW photovoltaic units, and a 15 MW storage plant, and the parameters are shown in Tables 10–12. The initial load of the system is 75 MW. The initial load of the system is 75 MW.

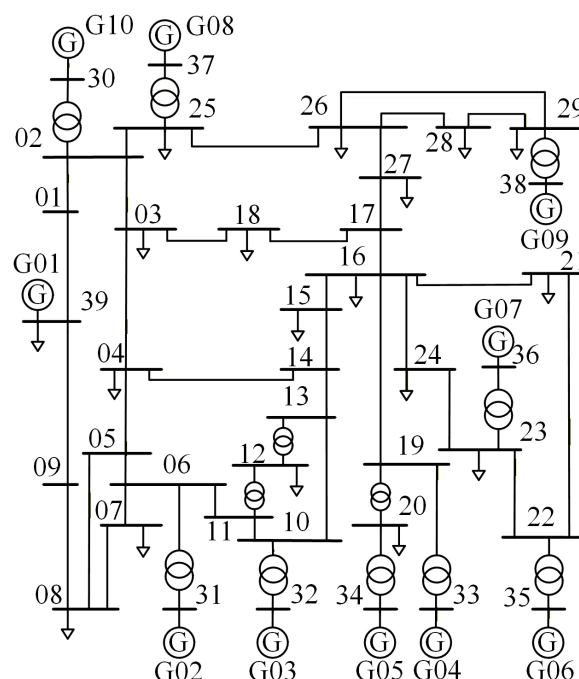


Figure 11. Single-line diagram of IEEE-39 system.

Table 10. Parameters of doubly-fed wind turbines.

Parameters of Doubly-Fed Fan	Parameter Values
Rated power	1 MW
Blade radius	35 m
Frequency control time constant	0.15 s
Asynchronous motor inertia time constant	1.92 s
Virtual inertia response time constant	5.5 s

Table 11. Parameters of photovoltaic unit.

PV Unit Parameters	Parameter Values
Rated power	1 MW
Standard solar intensity	1000 W/m ²
Battery material constants	0.0005
Power standby factor	0.1
Upper and lower deadband	±0.02 Hz

Table 12. Parameters of the energy storage plant.

Parameters of the Storage Plant	Parameter Values
Rated power	1 MW
Maximum state of charge	0.8 p.u.
Minimum state of charge	0.2 p.u.
Initial state of charge	0.6 p.u.
Upper and lower deadband	±0.03 Hz

- (1) New energy deadband and different perturbations under the PFR coefficient correction strategy on frequency regulation impact analysis simulation verification

In order to verify that the previous new energy PFR deadband and frequency deviation are positively off, in the IEEE39-node example model shown in Figure 11, the load's sudden reduction perturbation of 1.69 p.u. and 0.85 p.u. is set at 5 s, respectively, and the wind

power deadband is set to be 0.05 Hz, the photovoltaic deadband is set to be 0.02 Hz, and the energy storage deadband is set to be 0.03 Hz. The wind farm is accessed at the 29th node, and the energy storage is accessed at the 37th node, and the correction factor is 1.32 according to Equation (22). The wind farm is connected at node 29, energy storage at node 37, and photovoltaic plant at node 34, and the correction factor is 1.32 according to Equation (22). The simulation results are shown in Figures 12 and 13.

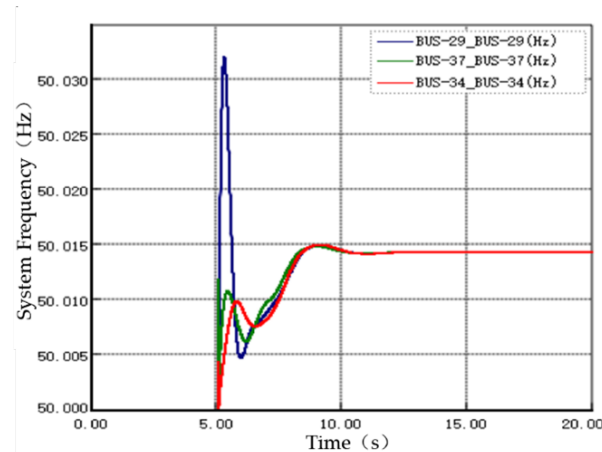


Figure 12. Simulation result graph of sudden load reduction of 1.69 p.u.

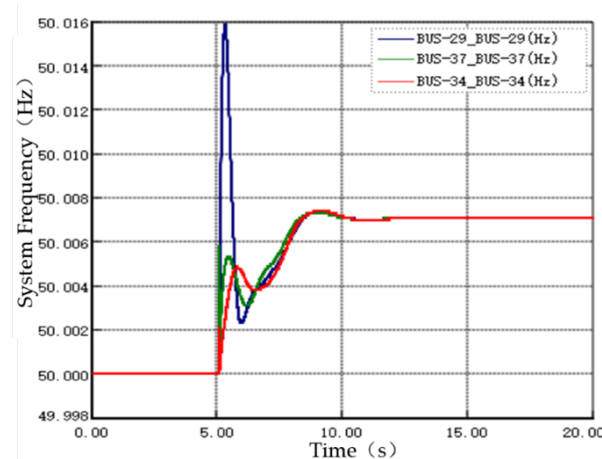


Figure 13. Simulation results of sudden load reduction of 0.85 p.u. after correcting the frequency regulation coefficient for once.

According to Figure 12, it can be seen that when the deadband of wind power, photovoltaic technology, and energy storage is set at a certain level, the smaller the deadband of the new energy PFR under the sudden load shedding perturbation, the smaller the maximum frequency deviation of the system, and the steady state frequency deviation is almost unaffected. According to Figure 13, it can be seen that the frequency increase is caused by the sudden load shedding at 5 s. At this point, by applying the corrected frequency regulation coefficient to perform a single frequency regulation, the system's maximum frequency deviation is improved. Compared to the maximum frequency deviation before correction, it is reduced by 0.0026 Hz, 0.0036 Hz, and 0.0034 Hz, respectively. Simultaneously, the peak frequency points are reduced by 0.016 Hz, 0.006 Hz, and 0.005 Hz, respectively.

(2) Verification of the effect of PFR factor correction in real wind farms

In order to verify the applicability of the above proposed frequency regulation factor correction strategy in the real power grid, a regional power grid model with high penetra-

tion of new energy is constructed in the Bonneville Power Administration (BPA) power system simulation software, which contains the distribution of power grid generation resources, load characteristics, and historical frequency data, and adopts the topology and load distribution characteristics of the real power grid. The model incorporates the distribution of power generation resources, load characteristics, and fundamental system data, including rated voltage and rated frequency, and adopts the actual wind farm topology, as illustrated in Figure 14. Wind farms participate in primary frequency regulation through a hierarchical cooperative control structure. Frequency at the grid connection point is sampled in real-time using frequency measurement devices and transmitted to the rapid frequency response unit. Based on predefined primary frequency regulation control strategies, the unit calculates the required active power adjustment for the wind farm and coordinates its distribution to individual wind turbines via the Energy Management System (EMS). The dispatch system and AGC system exchange information with the wind farm via a communication network, coordinating and constraining the frequency regulation process to enable rapid wind farm response to system frequency deviations.

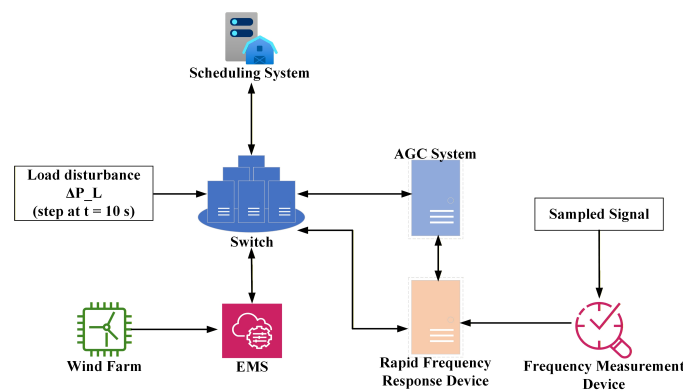


Figure 14. Topology of wind farm fast frequency response Function.

Based on the topology shown in Figure 14, the primary frequency regulation deadband of the wind farm is set to 0.03 Hz, with a limiting factor of 10% and a primary frequency regulation coefficient of 33. According to Equation (24), the modified main frequency regulation coefficient is calculated as 36.3. The wind farm participates in the main frequency regulation using a fast frequency response control algorithm. The frequency deviation at the grid connection point first undergoes deadband logic processing, followed by the generation of active power regulation signals through proportional-integral control combined with inertia simulation. The controller output is constrained by power saturation limits to ensure the safe operation of the wind farm. Actual operational data from a wind farm in Zhejiang Province is selected, with unit parameters shown in Table 13.

Table 13. Operating parameters of a wind farm in Zhejiang.

WTG Parameters	Parameter Values
Rated Voltage	0.69 kV
Rated power	11.5 MW
Share of wind turbine capacity	0.7
Number of units	96
Time constant	0.02 s
Active proportionality factor	0.1
Active integral factor	2
Inertia proportionality factor	10
Damping coefficient	1

The simulation was conducted using the BPA power system simulation software. The simulation environment is shown in Table 14, which models a regional grid with a high wind-power penetration rate. The wind farm was represented by an aggregated model comprising 96 wind turbines, with parameter configurations based on the actual operational data listed in Table 13. A step load disturbance was applied to the grid model at the 10 s mark, and the system frequency at the wind farm's grid-connected bus was monitored to evaluate primary frequency regulation performance. Simulation settings were selected to align with actual power system operating conditions. The system frequency simulation results before and after frequency regulation coefficient correction are shown in Figure 15.

Table 14. Simulation environment settings.

Item	Description
Simulation software	BPA
Grid model	Regional power grid
Wind power penetration	70%
Wind farm model	Aggregated model (96 WTGs)
Disturbance type	Load step
Disturbance time	10 s
Frequency monitoring	Wind farm grid connection bus

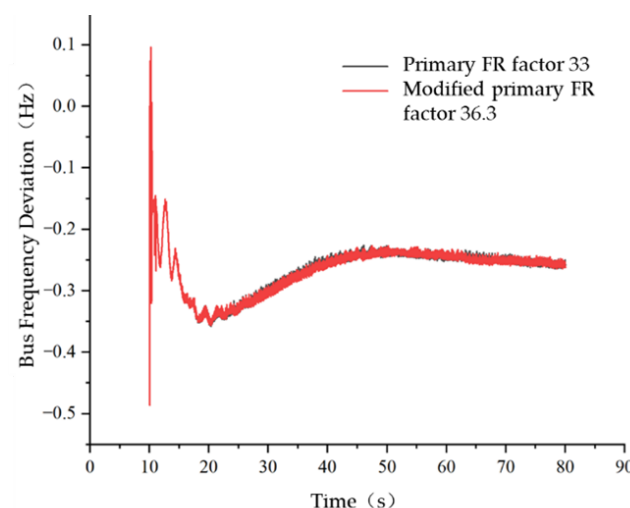


Figure 15. Comparison of system frequency before and after correction of PFR factor in wind farms.

According to Figure 15, it can be seen that the maximum frequency deviation can be further reduced after the PFR coefficient correction is carried out with no change in the PFR and limiting of wind power.

In summary, this section verifies the effect of different new energy frequency regulation deadband on the system PFR effect in the paper, verifies the effectiveness of the PFR coefficient correction strategy under different power perturbations, and further analyzes the applicability of the proposed coefficient correction strategy under the actual new energy field stations.

7. Conclusions

To enhance the grid integration and consumption capacity of new energy sources, it is essential to strengthen the frequency regulation capability of the power grid system itself, thereby ensuring the frequency stability of systems with high proportions of new energy sources. Based on an analysis of the frequency response model for new energy systems,

this paper considers the impact of integrating renewable energy sources such as wind, solar, and storage on grid frequency. It proposes a system frequency response expression incorporating both conventional frequency regulation deadband and step-type frequency regulation deadband and thoroughly examines the influence of key frequency regulation parameters on grid frequency characteristics. The specific conclusions are as follows:

(1) A conventional frequency regulation deadband can weaken the frequency regulation capabilities of renewable energy sources, with this effect becoming more pronounced as the proportion of renewable energy increases. Therefore, rationally designing a frequency regulation deadband can effectively mitigate its impact on renewable energy regulation capacity. This approach enhances the grid's ability to integrate renewable energy, reduces energy waste, and contributes to achieving energy conservation and emission reduction goals.

To address the adverse impact of conventional frequency regulation deadbands on the effectiveness of new energy frequency regulation, this paper proposes an optimized frequency regulation strategy based on maximum frequency deviation. By modifying the PFR coefficient, it effectively mitigates frequency deviation and enhances the frequency regulation performance of the power grid system.

(2) The extent of frequency limiting for renewable energy units directly impacts the magnitude and duration of frequency deviations during PFR. Together with the PFR coefficient, it influences the frequency deviation following system disturbances. Excessive limiting of frequency regulation capacity slows response times, reduces frequency recovery speed, and restricts the frequency regulation capability of renewable generation systems. Therefore, flexibly configuring deadband, frequency limits, and PFR coefficients ensures a sufficient frequency response capability while maintaining system stability. The optimized frequency regulation scheme not only enhances the integration capacity of renewable energy, but also reduces energy waste, thereby supporting the achievement of energy conservation and emission reduction goals. Simultaneously, it ensures efficient grid integration of renewable energy, promoting green, and low-carbon development.

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Nomenclature

Abbreviations

DFIG	Doubly Fed Induction Generator
IBRs	Inverter-based Resources
PFR	Primary Frequency Regulation
ESS	Energy Storage System
SOC	State of Charge
WTG	Wind Turbine Generator
SG	Synchronous Generator
RKE	Rotor Kinetic Energy

VSG	Virtual Synchronous Generator
BPA	Bonneville Power Administration
PSASP	Power System Analysis Software Package
Symbols	
Δf	Frequency deviation
f	System frequency
f_0	Rated system frequency
f_{ref}	System reference frequency
$\Delta f_{\text{virtual}}$	Virtual frequency deviation
F_H	Percentage of high-pressure cylinder output power relative to total turbine output
T_R	Intermediate reheat steam volume time constant for thermal power units
D	System damping coefficient
M	Inertial time constant
R	Static regulation coefficient of thermal power units
P_L	Load disturbance power
α	Wind turbine installed capacity share
β	Share of photovoltaic installed capacity
γ	Installed capacity share of energy storage units
ΔP_L	Step load disturbance amount
$\Delta P_w(t)$	Active power output of wind turbine
$\Delta P_s(t)$	Active power output of PV unit
$\Delta P_b(t)$	Active power output of energy storage
$\Delta P_t(t)$	Active power output of conventional thermal power units
ΔP_{max}	Maximum output power
P_{limit}	New energy frequency regulation limiting
P_N	Rated power capacity of new energy stations
k_w	PFR coefficient of wind turbine
k_s	PFR coefficient of PV unit
k_b	PFR coefficient of energy storage
k	General symbol for PFR coefficient
μ	Total share of new energy
c_0	Correction coefficient of PFR coefficient
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	Characteristic roots of system frequency dynamics
$C_1, C_2, C_3, C_4, C_5, C_6$	Integration constants in analytical frequency solution
t	Time variable
t_0	The moment the frequency drops into the deadband
t_1, t_2	Time points of deadband crossing
t_{max}	Time when maximum frequency deviation occurs
$\Delta f_{1,\text{max}}$	Maximum frequency deviation of standard systems
$\Delta f_{2,\text{max}}$	Maximum frequency deviation of step-type system
$\Delta f_{1,\infty}$	Steady-state frequency deviation of the system in the deadband
$\Delta f_{2,\infty}$	Steady-state frequency deviation of the system with step-type frequency regulation
Δf_{max}	Maximum frequency deviation
Δf_s	Special solution
$\Delta f(t)$	Dynamic frequency deviation over time
$\Delta f(t)_{\text{target}}$	Target maximum frequency deviation

References

1. Akram, U.; Nadarajah, M.; Shah, R.; Milano, F. A review on rapid responsive energy storage technologies for frequency regulation in modern power systems. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109626. [\[CrossRef\]](#)
2. Li, L.; Zhu, D.; Zou, X.; Hu, J.; Kang, Y.; Guerrero, J.M. Review of frequency regulation requirements for wind power plants in international grid codes. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113731. [\[CrossRef\]](#)

3. Zhu, D.; Zhang, Y.-J.A. Optimal coordinated control of multiple battery energy storage systems for primary frequency regulation. *IEEE Trans. Power Syst.* **2019**, *34*, 555–565. [\[CrossRef\]](#)
4. Gao, H.; Zhang, F.; Ding, L.; Cornélusse, B.; Zhang, G.; Salimu, A. Multi-segment droop control and optimal parameter setting strategy of wind turbine for frequency regulation. *Int. J. Electr. Power Energy Syst.* **2024**, *158*, 109968. [\[CrossRef\]](#)
5. Li, S.; Xu, Q.; Xia, Y.; Hua, K. Comprehensive setting and optimization of dead-band for BESS participation in power grid primary frequency regulation. *Int. J. Electr. Power Energy Syst.* **2022**, *141*, 108195. [\[CrossRef\]](#)
6. Aziz, A.; Oo, A.T.; Stojcevski, A. Frequency regulation capabilities in wind power plant. *Sustain. Energy Technol. Assess.* **2018**, *26*, 47–76. [\[CrossRef\]](#)
7. Pradhan, C.; Bhende, C.N.; Samanta, A.K. Adaptive virtual inertia-based frequency regulation in wind power systems. *Renew. Energy* **2018**, *115*, 558–574. [\[CrossRef\]](#)
8. Jiang, Y.; Zhao, S. Distributionally robust dispatch method with enhanced wind power frequency support modeling and inherent decision-dependent uncertainty. *Energy* **2025**, *333*, 137308. [\[CrossRef\]](#)
9. Zhang, H.; Zhang, F.; Salimu, A.; Zhang, G. Optimal parameter setting of wind farm for frequency regulation based on evaluation of available kinetic energy. *Electr. Power Syst. Res.* **2025**, *249*, 111997. [\[CrossRef\]](#)
10. Zhang, X.; Cao, Y.; Liu, H.; Fu, Y.; Huang, Y.; Li, Y. Virtual elastic coupling control of grid-forming wind farms for power oscillation suppression. *Energy* **2025**, *335*, 138180. [\[CrossRef\]](#)
11. Zhang, G.; Cheng, S.; Li, P.; Wang, H.; Cheng, X.; Ge, Y.; Yang, J. Coordinated control strategy of primary and secondary frequency responses of wind farm based on virtual synchronous generator technology. *Energy Rep.* **2025**, *13*, 6514–6524. [\[CrossRef\]](#)
12. Margaritis, I.D.; Papathanassiou, S.A.; Hatziargyriou, N.D.; Hansen, A.D.; Sørensen, P. Frequency control in autonomous power systems with high wind power penetration. *IEEE Trans. Sustain. Energy* **2012**, *3*, 189–199. [\[CrossRef\]](#)
13. Shu, H.; Wang, G.; Chen, J.; Ma, H.; He, T. Coordinated control of wind-storage combined with primary frequency regulation and variable coefficient based on wind speed and SOC. *J. Energy Storage* **2024**, *87*, 111356. [\[CrossRef\]](#)
14. Duan, J.; Zhang, Y.; Li, Z.; Tao, J.; Wang, J. Fast frequency response strategy for wind-storage systems based on improved torque limit control under energy perspective. *J. Energy Storage* **2025**, *111*, 115406. [\[CrossRef\]](#)
15. Wen, C.; Mo, J.; Li, J.; Zhou, J.; Wang, P. Research on wind-storage coordinated frequency regulation strategy of high permeability wind power connected to regional power grid. *Energy Rep.* **2023**, *9*, 774–785. [\[CrossRef\]](#)
16. Wang, W.; Cao, Y.; Wang, Y.; You, J.; Zhang, G.; Xiao, Y. Combined wind-storage frequency modulation control strategy based on fuzzy prediction and dynamic control. *Energy Eng.* **2024**, *121*, 3801–3823. [\[CrossRef\]](#)
17. Wang, C.; Yang, F.; Zhang, Z.; Qian, K.; Lin, H.; Cao, Y. Photovoltaic-storage coordinated support control technology based on primary frequency regulation requirements. *Energy Rep.* **2024**, *12*, 6126–6136. [\[CrossRef\]](#)
18. Liang, J.; Fan, H.; Cheng, L.; Rong, S.; Li, T.; Yu, T.; Wang, L. Control strategy for improving the frequency response characteristics of photovoltaic and energy storage systems based on VSG control. *Energy Rep.* **2024**, *11*, 2295–2305. [\[CrossRef\]](#)
19. Zhang, J.; Sun, P.; Dong, G.; Chen, Y. Adaptive power regulation-based coordinated frequency regulation method for PV and energy storage system. *J. Energy Storage* **2025**, *106*, 114794. [\[CrossRef\]](#)
20. Liu, Z.; Qin, L.; Yang, S.; Zhou, Y.; Wang, Q.; Zheng, J.; Liu, K. A comprehensive control strategy for photovoltaic virtual synchronous generator considering frequency regulation capability. *Energy Rep.* **2022**, *8*, 153–163. [\[CrossRef\]](#)
21. Gao, H.; Zhang, F.; Ding, L.; Zhang, G.; Yang, L.; Salimu, A. Towards non-virtual inertia control of renewable energy for frequency regulation: Modeling, analysis and new control scheme. *Int. J. Electr. Power Energy Syst.* **2024**, *162*, 110314. [\[CrossRef\]](#)
22. Amir, M.; Singh, K. Frequency regulation strategies in renewable energy-dominated power systems: Issues, challenges, innovations, and future trends. In *Advanced Frequency Regulation Strategies in Renewable-Dominated Power Systems*; Academic Press: Cambridge, MA, USA, 2024; pp. 367–381.
23. Xin, H.; Liu, Y.; Wang, Z.; Gan, D.; Yang, T. A new frequency regulation strategy for photovoltaic systems without energy storage. *IEEE Trans. Sustain. Energy* **2013**, *4*, 985–993. [\[CrossRef\]](#)
24. Li, P.; Hu, W.; Hu, R.; Huang, Q.; Yao, J.; Chen, Z. Strategy for wind power plant contribution to frequency control under variable wind speed. *Renew. Energy* **2019**, *130*, 1226–1236. [\[CrossRef\]](#)
25. Fan, C.; Chen, G.; Chen, Z.; Shi, H.; Liu, C.; Teng, Y. Frequency oscillation analysis of power system with multiple governor deadbands. *IEEE Access* **2020**, *8*, 88085–88092. [\[CrossRef\]](#)
26. Mohseni, M.; Islam, S.M. Review of international grid codes for wind power integration: Diversity, technology and a case for global standard. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3876–3890. [\[CrossRef\]](#)
27. Peng, Q.; Yang, Y.; Liu, T.; Blaabjerg, F. Coordination of virtual inertia control and frequency damping in PV systems for optimal frequency support. *CPSS Trans. Power Electron. Appl.* **2020**, *5*, 305–316. [\[CrossRef\]](#)

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