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Research on a Grid-Forming Frequency Regulation Control Strategy with Adaptive Damping and Inertia Based on Linear Active Disturbance Rejection Control (LADRC)

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Abstract: To address the insufficient frequency support capability of power systems with high wind power penetration and the degraded control performance of wind-storage hybrid systems caused by parameter coupling during frequency regulation, a damping- and inertia-adaptive grid-forming (GFM) energy-storage frequency regulation strategy based on linear active disturbance rejection control (LADRC) is proposed. First, on the basis of fast angular-frequency control using LADRC, damping and inertia adaptive loops are introduced to eliminate parameter coupling and enhance the system's frequency support capability. Meanwhile, considering the parameter characteristics of the GFM energy-storage frequency regulation strategy, a small-signal model from angular frequency and reference power to output power is established, and the transfer functions of the control loops are derived to achieve optimization of the system's frequency regulation performance. Finally, MATLAB simulations are conducted to compare the system responses of different control methods under identical operating conditions and wind-turbine output variations. The results demonstrate that the proposed control strategy can significantly enhance the frequency support capability of the wind-storage hybrid system under complex operating conditions.

Keywords: Grid-forming Energy Storage; Adaptive Control; Active Disturbance Rejection Control; Frequency Regulation

0 Introduction

In recent years, with the continuous advancement of energy transition and the implementation of the “dual-carbon” targets, the penetration level of wind power in power systems has increased rapidly[1,2]. However, most wind turbine generators are grid-connected through power electronic converters, whose output power is stochastic and fluctuating, and they lack the inherent rotational inertia and damping characteristics of synchronous generators[3,4]. As a result, the overall system inertia decreases significantly, and the frequency stability of the power grid is further weakened[5,6]. Under high wind power penetration, both the magnitude and duration of frequency deviations increase noticeably, raising the risk of frequency excursions[7,8]. Therefore, enhancing the system's frequency support capability has become essential.

Energy storage systems, owing to their fast response and bidirectional regulation capability, are considered an effective means to improve frequency stability[9,10]. Among them, grid-forming (GFM) energy storage can actively establish voltage and frequency and provides virtual synchronous characteristics, offering clear advantages over grid-following (GFL) control especially under weak-grid conditions[11,12]. However, in coordinated wind-storage operation, the control parameters of the storage system exhibit coupling, and virtual inertia and damping cannot adapt to system states, thereby affecting frequency regulation performance[13–16].

In recent years, research on improving VSG performance has continued to advance. Ref.[17] introduces a new VSG control method using lead-lag compensation, which effectively suppresses active-power overshoot under differential-gain

constraints; however, independent tuning of the damping term is not achieved, potentially causing high-frequency harmonic amplification. Refs.[18,19] incorporate active-power lag control into the VSG framework and design feedforward/feedback compensation around the damping parameter, but no systematic procedure for dominant-pole tuning is provided. Ref.[20] simplifies the original high-order active-power loop into a second-order model via equivalent order-reduction and offers a damping-optimization method. Ref.[21] develops a grid-forming wind-turbine frequency-regulation method with online-tunable control parameters based on a small-signal model, improving operational flexibility, but without analyzing virtual damping and virtual inertia. Ref.[22] places both virtual inertia and virtual damping within an automatic-adjustment framework, yet their inherent coupling remains unresolved. Refs.[23–26] consider the joint influence of inertia and damping on system frequency behavior and propose parameter-setting approaches, but do not reveal parameter interactions or their impact on system-level stability using a small-signal model. Overall, existing studies have not simultaneously achieved coordinated tuning of virtual inertia and virtual damping nor addressed their parameter-coupling issues.

Based on this, this paper proposes a damping- and inertia-adaptive grid-forming energy storage frequency regulation strategy based on Linear Active Disturbance Rejection Control (LADRC). LADRC employs an Extended State Observer (ESO) to estimate and compensate internal and external disturbances in real time, featuring simple structure, few parameters, and good dynamic performance. Building upon LADRC-based fast angular-frequency control, adaptive damping and inertia regulation is introduced, enabling the storage system to dynamically adjust virtual inertia and damping according to grid conditions, thereby enhancing frequency support and mitigating parameter coupling effects. Meanwhile, a small-

signal model from angular frequency and reference power to output power is established to analyze the influence of control parameters on frequency regulation performance, providing a theoretical basis for parameter tuning.

Finally, MATLAB-based simulations considering multiple operating scenarios, including step load disturbances and wind turbine output variations, are conducted. Results show that, compared with traditional control strategies, the proposed LADRC-based damping- and inertia-adaptive GFM control method significantly improves grid frequency support and exhibits superior dynamic performance and robustness. In summary, the proposed adaptive GFM energy storage control strategy effectively addresses the insufficient frequency support and parameter coupling issues under high wind-power penetration, providing a feasible technical solution and theoretical reference for the application of grid-forming energy storage in high-renewable power systems.

1 Wind–Storage Coordinated System Model

1.1 Modeling of the Wind–Storage Coordinated System

In this paper, an optimized grid-forming energy storage control strategy is proposed based on a frequency regulation system model composed of a wind–storage coordinated system and the utility grid, as shown in Fig. 1[27]. In this system, the wind turbine generator is connected to the battery energy storage system (BESS) through Bus 3, while the aggregated load is connected to Bus 4. The BESS can not only monitor key operating parameters such as system frequency in real time, but also respond and regulate rapidly in the presence of external disturbances, thereby effectively maintaining frequency stability and dynamic balance in modern power systems[28]. In addition, the structure of the wind–storage coordinated system is illustrated in Fig. 2.

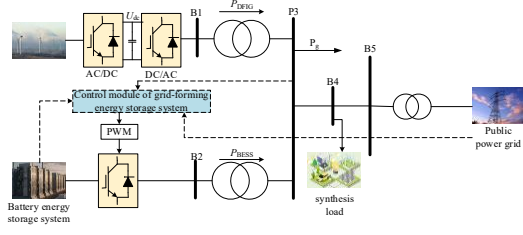


Fig. 1 Frequency Regulation System Model of the Wind-Storage Coordinated System and the Utility Grid

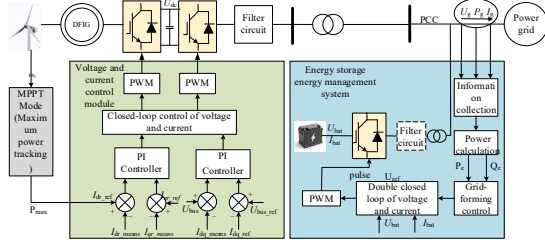


Fig. 2 Structure of the Wind-Storage Coordinated System

1.2 Modeling of the Grid-Forming Energy Storage Control System

The dynamic response of a traditional synchronous generator can be described by a second-order rotor swing equation. Since the rotor kinetic energy varies synchronously with the system frequency, when a mismatch between mechanical input power and electromagnetic output power causes a frequency deviation, the rotor provides inertia support by releasing or absorbing energy to the grid[29]. Grid-forming control based on the virtual synchronous generator (VSG) combines droop control with the rotor swing equation, reproducing the external characteristics of a synchronous generator and enabling wind and photovoltaic units to provide equivalent virtual inertia and damping[30]. A typical GFM control scheme is shown in Fig. 3, consisting of an outer power loop and an inner voltage-current dual-loop controller.

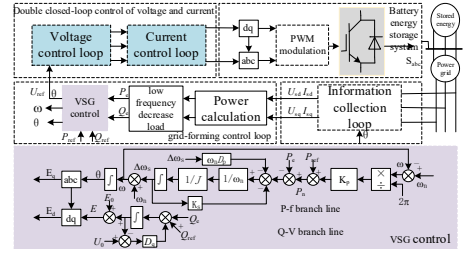


Fig. 3 Control Block Diagram of a Typical Grid-Forming System

The second-order rotor swing equation of a synchronous generator is given in (1), where the meanings of the variables are as follows: J denotes the virtual moment of inertia, and ω is the output angular frequency of the VSG. T_m and T_e represent the mechanical torque and electromagnetic torque, respectively. D_p and D_q are the damping coefficients of the P-f channel and Q-V channel, respectively. ω_n is the nominal angular frequency of the system. P_{ref} and Q_{ref} are the active and reactive power references of the VSG, while P_e and Q_e are the active and reactive powers calculated from voltage and current measurements at the PCC. k_e is the gain coefficient of the synchronous voltage, and E denotes the amplitude of the VSG output electromotive force. s is the Laplace operator. U_n represents the rated grid-side voltage amplitude, and U_0 is the measured grid-side AC voltage amplitude.

$$\begin{cases} = T_m - T_e - D_p(\omega - \omega_n) \\ = \frac{P_{ref}}{\omega_n} - \frac{P_e}{\omega_n} - D_p(\omega - \omega_n) \\ = (Q_{ref} - Q_e) + D_q(U_n - U_0) \\ = \frac{1}{J_s} [D_p(\omega_n - \omega) + (P_{ref} - P_e)] \end{cases} \quad (1)$$

Through analysis of the typical VSG control block diagram, it can be observed that both the active power reference P_{ref} and the grid-side angular frequency ω_r influence the active power P_e . The small-signal models from ω_r and P_{ref} to P_e , denoted as G_{Pref1} and G_{ω_r1} , are constructed as shown in (2).

$$\begin{cases} G_{Pref1} = \frac{\Delta P_e}{\Delta P_{ref}} |_{\Delta \omega_r=0} = \frac{k_e}{J\omega_n s^2 + (D_p\omega_n + k_s)s + k_e} \\ G_{\omega_r1} = \frac{\Delta P_e}{\Delta \omega_r} |_{\Delta P_{ref}=0} = -\frac{J\omega_n k_e s + k_e(D_p\omega_n + k_s)}{J\omega_n s^2 + (D_p\omega_n + k_s)s + k_e} \end{cases} \quad (2)$$

In the equation, $\Delta\omega_r = \omega_r - \omega_n$ is the feedback coefficient of the active-power–frequency branch; and the system oscillation angular frequency ω_1 and damping ratio ζ_1 are expressed as:

$$\begin{cases} \omega_1 = \sqrt{k_e/(J\omega_n)} \\ \zeta_1 = \frac{k_s + D_p\omega_n}{2} \sqrt{1/(k_e J\omega_n)} \end{cases} \quad (3)$$

When $\omega_r - \omega_n \neq 0$, the steady-state error of the active power output can be obtained from (2) as:

$$\text{Lim}_{G_{\omega_r}} \Delta\omega_r = -(k_s + \omega_n D_p) \Delta\omega_r \quad (4)$$

From (3), it can be observed that increasing D_p enhances the damping ratio ζ_1 , thereby improving the stability of the system response; conversely, decreasing D_p weakens the stability. In combination with (4), it is further evident that D_p and K_s exhibit significant coupling and jointly influence the steady-state error of the active power output. Therefore, proper configuration of these two parameters is essential for overall system performance; however, under complex operating conditions, it is difficult to optimize them simultaneously, requiring trade-offs among multiple performance indicators.

1.3 Principle of Inertia and Damping Parameter Tuning for Grid-Forming Energy Storage Systems

With the increasing penetration of wind power, conventional grid-forming VSG control becomes insufficient to constrain frequency deviations under high renewable integration. Given the tunable parameters of VSG, adaptive algorithms can dynamically adjust the equivalent inertia and damping at different stages of the frequency response under active-power disturbances, thereby enhancing transient regulation and disturbance rejection. To reasonably configure the GFM parameters, it is necessary to segment the frequency evolution process.

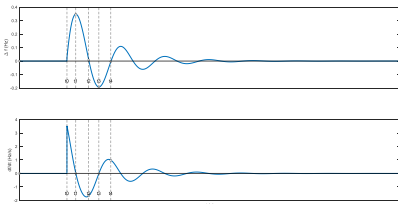


Fig. 4 Frequency waveform of the VSG within a single oscillation cycle

As shown in Fig. 4, after an active-power disturbance of the wind turbine occurs at t_0 , the frequency deviation and the rate of change of frequency (RoCoF) exhibit typical oscillatory behavior, which can be divided into four intervals from t_0 to t_4 . In Interval 1 ($\Delta f > 0$, $df/dt > 0$), the frequency rises; thus, increasing the equivalent inertia J helps suppress the rising slope, while the damping coefficient D_p limits overshoot. In Interval 2 ($\Delta f > 0$, $df/dt < 0$), the frequency begins to fall back, and moderately reducing J and D_p accelerates recovery. Interval 3 ($\Delta f < 0$, $df/dt < 0$) mirrors Interval 1, where increasing J suppresses negative overshoot and D_p adjusts the extremum. Interval 4 ($\Delta f < 0$, $df/dt > 0$) corresponds to Interval 2, where reducing J and D_p facilitates faster return. The detailed tuning directions are summarized in Table 1.

Table 1 Damping and Inertia Adjustments for Different Frequency Variation Intervals

Interval	Δf	df/dt	$\Delta f(df/dt)$	J	D_p
1	>0	>0	>0	Increase	Increase
2	>0	<0	<0	Decrease	Moderately decrease
3	<0	<0	>0	Increase	Increase
4	<0	>0	<0	Decrease	Moderately decrease

Based on the discussions in this section and the previous subsection, to enhance the frequency support and disturbance rejection capability of the wind power generation system under disturbances and to reduce the coupling between parameters, this paper proposes a damping and inertia adaptive

control strategy based on LADRC.

2 Research on Damping and Inertia Adaptive Grid-Forming Frequency Regulation Control Strategy Based on LADRC

2.1 Damping and Inertia Adaptive Strategy Based on LADRC

According to the frequency variation characteristics summarized in Table 1, an exponential function is employed to establish a dynamic relationship between the virtual inertia, damping coefficient, and the rate of change of frequency (RoCoF) as well as the frequency deviation. In this way, the system can continuously track frequency fluctuations and automatically adjust and optimize the control parameters, thereby reducing the sensitivity of inertia and damping, and effectively enhancing the dynamic frequency response capability of the wind turbine generator under active power disturbances. The mathematical model of this control loop is expressed in (5) and (6).

$$D_p = \begin{cases} D_0, & |\Delta f| < N \\ D_0 + e^{k_3|\Delta f|}, & |\Delta f| \geq N \end{cases} \quad (5)$$

$$J = \begin{cases} J_0, & \left| \frac{df}{dt} \right| < M \\ J_0 + e^{k_1 \left| \frac{df}{dt} \right|}, & \Delta f \frac{df}{dt} > 0 \cap \left| \frac{df}{dt} \right| > M \\ J_0 - e^{k_2 \left| \frac{df}{dt} \right|}, & \Delta f \frac{df}{dt} < 0 \cap \left| \frac{df}{dt} \right| > M \end{cases} \quad (6)$$

According to the frequency characteristics in Table 1, an exponential function is used to establish the dynamic relationship between the virtual inertia, damping coefficient, the rate of change of frequency (RoCoF), and the frequency deviation. This enables the system to track frequency fluctuations in real time and automatically adjust the control parameters, thereby increasing the sensitivity of inertia and damping and improving the frequency response capability of the wind turbine under power disturbances. The mathematical models of this control mechanism are shown in (5) and (6), where J_0 and D_0 denote

the steady-state inertia constant and damping constant, respectively; M and N are the RoCoF and frequency deviation thresholds; k_1 , k_2 , and k_3 are tuning coefficients; Δf and df/dt represent the frequency deviation and the rate of change of frequency, respectively.

Equation (6) describes the inertia adaptive regulation. When $|df/dt| < M$, the frequency varies slowly and the inertia remains at J_0 . When $|df/dt| \geq M$, the inertia is increased or decreased adaptively according to the deviation direction to suppress the frequency change rate and the peak deviation. Equation (5) defines the damping adaptive model. When $|\Delta f| < N$, the damping coefficient remains at D_0 ; when $|\Delta f| \geq N$, the damping increases with $|\Delta f|$, enhancing the suppression of further frequency deviation and reducing the maximum frequency excursion.

The Linear Active Disturbance Rejection Controller (LADRC) consists of three components: the Tracking Differentiator (TD), the Linear Extended State Observer (LESO), and the Linear State Error Feedback (LSEF). Its core concept is to actively estimate and compensate system disturbances in real time. LADRC does not rely on an accurate mathematical model of the system; instead, it observes the total disturbance online (including external disturbances and model uncertainties) and compensates for it in the control loop, thereby achieving fast and smooth control. Compared with the traditional PID controller, LADRC has a more systematic structure and can significantly enhance dynamic response, disturbance rejection capability, and steady-state accuracy.

Under complex operating conditions of grid-forming energy storage systems, the strong coupling between D_p and k_s makes it difficult to simultaneously achieve oscillation suppression and steady-state deviation control. Introducing LADRC effectively resolves this issue and ensures satisfactory dynamic response performance of the energy storage system. Based on this analysis, this paper proposes a damping and inertia adaptive

control strategy based on LADRC, enabling the system to maintain high frequency regulation accuracy and dynamic stability under disturbances such as wind power fluctuations and load variations. The proposed strategy mitigates the impact of external disturbances on power balance, reduces errors caused by PLL complexity, and provides the required virtual inertia support to achieve fast energy allocation. Consequently, it significantly improves grid frequency regulation quality and enhances system safety and stability under extreme operating conditions. The control block diagram of the proposed strategy is shown in Fig. 5.

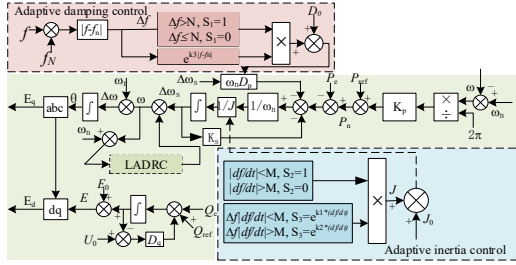


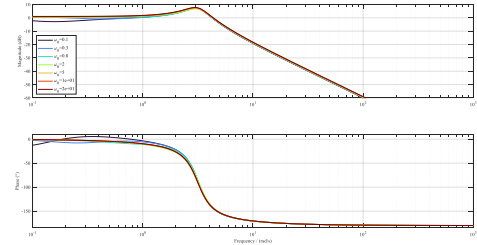
Fig. 5 Block Diagram of the LADRC-Based Damping and Inertia Adaptive Grid-Forming Control Strategy

2.2 Performance Analysis of the Control Strategy

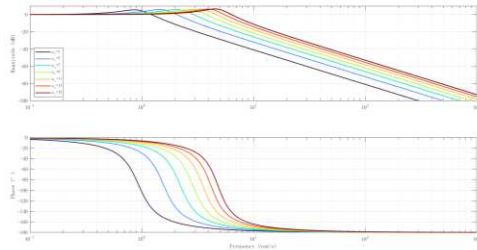
Based on the control strategy block diagram, the active power–frequency loop in the Virtual Synchronous Generator (VSG) control is selected as the primary control objective, with the angular frequency ω serving as the reference input. The Linear State Error Feedback (LSEF) utilizes output observation and error feedback to perform disturbance compensation on the controlled variable, enabling the system output to track the reference input in real time. Accordingly, the Bode plot of the control system is obtained, as shown in Fig. 6.

In Fig. 6, ω_0 denotes the ESO bandwidth, and ω_c denotes the controller bandwidth. To analyze their individual impacts on system performance, $\omega_c=10$ is first fixed while ω_0 varies from 0.1 to 10, as shown in Fig. 6(a). The results indicate that, as

ω_0 increases, the high-frequency suppression exhibits a “weak–strong” trend. When ω_0 is small, the low-frequency phase margin fluctuates significantly, affecting stability; for medium values, the disturbance attenuation and phase margin in the mid-frequency range decrease simultaneously, while the high-frequency characteristics improve; when ω_0 is too large, the overall disturbance rejection becomes weaker and the high-frequency phase margin further decreases. According to the Bode-plot performance, $\omega_0 \approx 3$ provides a favorable compromise between disturbance rejection and phase margin. With $\omega_0=3$ fixed, increasing ω_c (from 3 to 15) in Fig. 6(b) shows that a higher ω_c continuously enhances disturbance rejection, improves the mid-frequency phase margin, and strengthens low-frequency disturbance attenuation, thereby increasing the system robustness to external perturbations. Based on this analysis, $\omega_0=3$ and $\omega_c=3$ are adopted considering their coordination.



(a) Bode plot of the control system when ω_0 increases



(b) Bode plot of the control system when ω_c increases

Figure 6 Bode plots of the control system

Next, the overall transfer function of the P–F control loop is derived, and the small-signal model from the reference active power P_{ref} to the output

active power P_e , denoted as G_{Pref1} , is obtained. In addition, the small-signal model from the grid-side angular frequency ω_r to the output active power, denoted as $G_{\omega r2}$, is also derived, with the expressions given in (7).

$$\begin{cases} G_{Pref2} = \frac{\Delta P_e}{\Delta P_{ref}}|_{\Delta \omega_r=0} = \frac{k_e k_g k_a \tau_s s + k_e k_g (k_a - k_b)}{J \omega_n \tau_s s^3 + (\tau_s k_s + \tau_s D_p \omega_n + J \omega_n) s^2 + (k_s + D_p \omega_n + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \\ G_{\omega r2} = \frac{\Delta P_e}{\Delta \omega_r}|_{\Delta P_{ref}=0} = \frac{-k_e [J \omega_n \tau_s s^2 + (\tau_s k_s + J \omega_n + \tau_s D_p \omega_n) s + k_s + D_p \omega_n]}{J \omega_n \tau_s s^3 + (\tau_s k_s + \tau_s D_p \omega_n + J \omega_n) s^2 + (k_s + D_p \omega_n + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \end{cases} \quad (7)$$

In this expression, k_g denotes the feed-forward deviation gain coefficient, τ_s represents the deviation time constant, k_a is the feed-forward gain coefficient, and k_b denotes the deviation gain coefficient. To eliminate the influence of the damping parameter, the damping coefficient D_p in (7) is set to zero, yielding (8).

$$\begin{cases} G_{Pref2} = \frac{\Delta P_e}{\Delta P_{ref}}|_{\Delta \omega_r=0} = \frac{k_e k_g k_a \tau_s s + k_e k_g (k_a - k_b)}{J \omega_n \tau_s s^3 + (\tau_s k_s + J \omega_n) s^2 + (k_s + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \\ G_{\omega r2} = \frac{\Delta P_e}{\Delta \omega_r}|_{\Delta P_{ref}=0} = \frac{-k_e [J \omega_n \tau_s s^2 + (\tau_s k_s + J \omega_n) s + k_s]}{J \omega_n \tau_s s^3 + (\tau_s k_s + J \omega_n) s^2 + (k_s + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \end{cases} \quad (8)$$

By comparing (2) with (8), it can be seen that after introducing the LADRC stage, the pole-zero locations of the active power-frequency branch closed-loop system in the conventional grid-forming energy storage control are reshaped, thereby modifying the dynamic response characteristics of the output active power P_e . Based on the small-signal model analysis, the terms that have a negligible impact on system stability—namely, the parameter terms in (9) that contain only τ_s but do not include k_g —are omitted, yielding the simplified small-signal model G_{P2} , as shown in (10).

$$\begin{cases} G_{P2} = \frac{k_e k_g k_a \tau_s s}{J \omega_n s^2 + (k_s + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \\ + \frac{k_e k_g (k_a - k_b)}{J \omega_n s^2 + (k_s + k_e k_g k_a \tau_s) s + k_e k_g (k_a - k_b)} \end{cases} \quad (10)$$

At this moment, the system oscillation angular frequency ω_2 and damping ratio ξ_2 are given by

(11).

$$\begin{cases} \omega_2 = \sqrt{\frac{k_e k_g (k_a - k_b)}{J \omega_n}} \\ \xi_2 = \frac{D_p \omega_n + k_e k_g k_a \tau_s + k_s}{2 \sqrt{k_e k_g (k_a - k_b) J \omega_n}} \end{cases} \quad (11)$$

For the second-order system shown in (10), when the damping ratio is less than 1, the system tends to exhibit a large oscillation amplitude and a relatively long settling time. To improve the dynamic performance, the damping ratio is generally required to be no less than 1. Based on this requirement, (11) can be rearranged to obtain (12).

$$k_g \tau_s \geq \frac{-(k_s + D_p \omega_n) + 2 \sqrt{2 k_e k_g (k_a - k_b) J \omega_n}}{k_e k_a} \quad (12)$$

Based on (12) and Table 2, the Bode diagram of the traditional grid-forming energy storage control strategy can be obtained, as shown in Fig. 7. Following the same approach, the Bode diagrams and root locus plots of parameters k_a and k_b under different inertia parameter settings for the proposed scheme can be derived. The corresponding results are shown in Fig. 8 and Fig. 9, respectively.

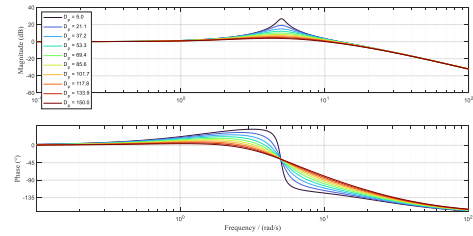
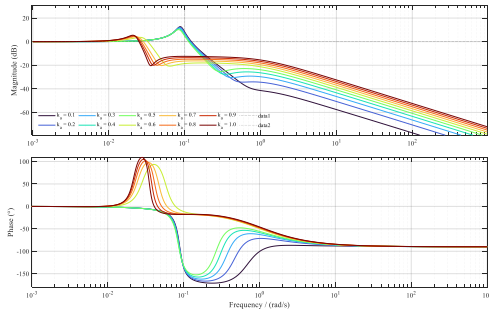


Fig. 7 Bode diagram of the traditional grid-forming energy storage control system

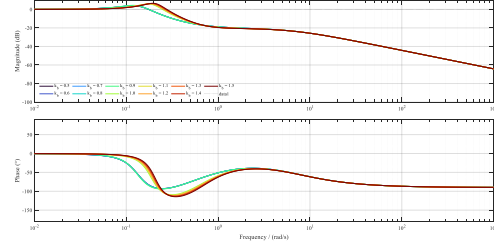
The analysis shows that in traditional grid-forming energy storage control, increasing the damping parameter D_p from 5 to 150 significantly suppresses disturbance amplitude and improves high-frequency stability, while slightly reducing the low-frequency phase margin. Since D_p is coupled with the active power-frequency branch parameter k_s , it is difficult to optimize both simultaneously; therefore, the LADRC-based damping and inertia adaptive grid-forming energy storage frequency regulation strategy are introduced.

When the adjustment parameter k_a increases from 0.1 to 1 ($k_b = 0.5$), the overall phase margin decreases and the high-frequency disturbance suppression weakens. If k_a is too large or too small, signal amplification appears in the mid-frequency range. When k_a approaches k_b , both disturbance suppression and phase margin are improved. Under $k_a=1$, increasing k_b enhances the high-frequency phase margin, but once $k_b > k_a$, the suppression capability begins to deteriorate. Therefore, the parameters should satisfy $k_b < k_a$, and the system performance is optimal when the two values are close. From Fig. 7–Fig. 8, the traditional control strategy only begins to suppress disturbances at approximately 1 rad/s and exhibits pronounced oscillations near the fundamental frequency, which cannot meet modern grid frequency-stability requirements. In contrast, the proposed strategy starts attenuating disturbances at around 10^{-1} rad/s, significantly increases the phase margin, and greatly enhances system stability.

In summary, with proper parameter configuration, the LADRC-based damping and inertia adaptive grid-forming energy storage frequency regulation strategy can rapidly respond to frequency deviation and provide effective frequency support. It resolves the difficulty of balancing oscillation suppression and steady-state error caused by the coupling between D_p and k_s in traditional control, while significantly enhancing the system's disturbance-rejection capability and operational stability.



(a) Bode diagram of the control system with varying k_a



(b) Bode diagram of the control system with varying k_b

Figure 8. Bode diagram of the control system

3 Simulation Verification

Based on the proposed model and the parameters in Table 2, a wind-storage coordinated frequency regulation simulation system is established, in which the BESS adopts the LADRC-based damping and inertia adaptive grid-forming control strategy. The system consists of a 300 MW wind turbine generator and a 100 MW/300 MWh BESS. Two typical disturbance scenarios are considered: step load disturbance and wind power variation. By comparing the proposed strategy with the traditional LADRC and the conventional grid-forming control, the system is evaluated in terms of frequency response, frequency regulation accuracy, and dynamic performance.

Table 2 System Simulation Parameters

Meaning	Parameter	Value
System Reference	ω_n	0.1
Angular Frequency	(rad/s)	
Initial State of		
Charge of the	S_{ocl}	0.75
Energy Storage		
System		
Active Power		
Branch Feedback	k_s	0.15
Coefficient		
Feedforward		
Deviation Gain	k_g	0.4
Coefficient		
Rated Power of the		
Wind Turbine	P_{DFIG}/W	2×10^8
Generator		

Continued Table2 System Simulation

Parameters		
Meaning	Parameter	Value
Feedforward Gain Coefficient	k_a	1
Rated Frequency of the Power System	f/Hz	50
Deviation Gain Coefficient	k_b	0.9
Inertia Setting Value	$J_0(\text{kg}\cdot\text{m}^2)$	60
Damping Setting Value	$D_0(\text{N}\cdot\text{m}\cdot\text{s}/\text{rad})$	0.1

3.1 Step Load Disturbance Condition

In the active disturbance rejection control, the parameters are set as $\omega_0 = 3 \text{ rad/s}$, $\omega_c = 15 \text{ rad/s}$, and $b_0 = 4$, with the remaining parameters listed in Table 2. The output power under a load step disturbance is shown in Fig. 9. The traditional grid-forming energy storage control exhibits a relatively slow dynamic response and limited high-frequency disturbance attenuation, while the conventional LADRC improves response speed and disturbance rejection. With the proposed LADRC-based damping and inertia adaptive control strategy, the system dynamics are further enhanced, showing faster response and stronger disturbance rejection. As shown in Fig. 9, the proposed strategy achieves an overshoot of $|H_{\max}| = 0.1096$, which is reduced by 32.8% compared with conventional LADRC (0.1631) and by 33.9% compared with the traditional grid-forming control (0.1658), and the steady-state recovery time is also significantly shorter. These results demonstrate that the proposed strategy markedly improves the system's dynamic response and stability under load step disturbances, providing superior frequency regulation and disturbance rejection performance.

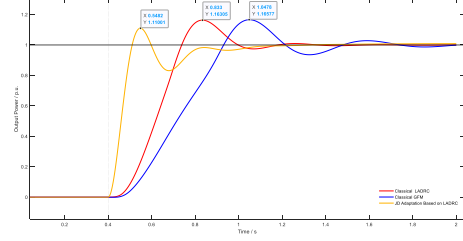


Figure 9. Dynamic response of the system under step load disturbance condition

3.2 Wind Turbine Output Variation Condition

Figure 10 shows the frequency support comparison under wind turbine power variations. The wind speed is initially 8 m/s, increases to 10 m/s at 2.5 s, and drops back to 8 m/s at 3.5 s. When the active power suddenly increases, the proposed LADRC-based damping and inertia adaptive strategy achieves the best performance, with a frequency overshoot of 50.038 Hz, compared with 50.043 Hz under traditional LADRC and 50.055 Hz under traditional GFM control. Similarly, when the active power decreases, the proposed strategy still provides the best regulation performance. These results demonstrate its clear advantage in frequency support.

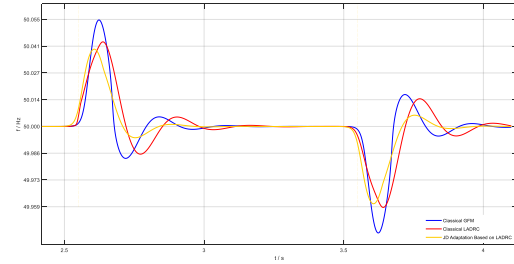


Figure 10. Dynamic response under wind turbine output variation scenario

4 Conclusion

This paper proposes a damping- and inertia-adaptive grid-forming energy storage frequency regulation strategy based on LADRC. The coupling among key parameters of the energy storage system is analyzed using control principles and small-signal modeling, and a feedforward deviation term is added to the active-power-frequency control channel to enhance the dynamic

response of the active-power reference and mitigate adverse parameter coupling. A damping and inertia adaptive loop is further designed based on system frequency dynamics and exponential functions to improve response speed and robustness. Under step disturbances and wind power fluctuations, the proposed strategy demonstrates superior frequency regulation performance compared with traditional methods, effectively enhancing grid frequency support capability and improving system stability.

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