

Article

Cooperative Control of Dynamic Power Decoupling and Adaptive Damping–Inertia for Grid-Forming Converters

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Abstract

Aiming at the problems of the severe active–reactive power coupling, insufficient adaptive inertia–damping regulation, and degraded dynamic performance of virtual synchronous generators (VSGs) under the operating conditions of a weak grid, high resistance-to-reactance ratio, and large power angle, this paper proposes a cooperative control strategy that combines reactive power feedforward decoupling with adaptive damping–inertia regulation. First, a small-signal power model of the VSG is established, and a dynamic relative gain array is employed to quantitatively analyze the effects of the resistance-to-reactance ratio and power angle on power coupling characteristics, revealing that large power angles and high resistance-to-reactance ratios significantly aggravate active–reactive power coupling. Based on this analysis, a reactive-power-oriented feedforward decoupling strategy is designed to suppress the cross-coupling between reactive power and power angle while preserving the intrinsic inertia support characteristics of the active power loop. Eigenvalue migration analysis further demonstrates that the proposed reactive-power-oriented decoupling provides higher damping ratios and larger stability margins than conventional full active–reactive power decoupling. Furthermore, a deep deterministic policy gradient-based adaptive damping–inertia control method is developed by incorporating frequency deviation, power fluctuation, voltage deviation, and coupling degree into the state space, enabling the online coordinated optimization of virtual inertia and damping coefficients. The hardware-in-the-loop experimental results verify that the proposed strategy effectively suppresses active–reactive power coupling, reduces power overshoot and oscillation, enhances frequency support capability and dynamic response speed, and maintains superior stability under weak grid conditions. Sensitivity analysis under grid impedance estimation errors further confirms its strong robustness against parameter uncertainty, while tests under composite disturbance scenarios demonstrate excellent transient performance. The proposed strategy provides an effective solution for improving the grid-connected operation performance and adaptability of VSGs in low-inertia power systems.



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Keywords: virtual synchronous generator; power decoupling; reactive power directional compensation; adaptive inertia and damping; deep deterministic policy gradient

1. Introduction

The penetration rate of renewable energy sources such as wind power and photovoltaic power in power systems keeps increasing. A large number of power electronic

converters have replaced traditional synchronous generator sets, which has led to a significant reduction in the equivalent rotational inertia and continuous deterioration of the damping characteristics of power grids. Consequently, the system is prone to rapid frequency drop, power oscillation and other issues under disturbances, seriously endangering the safe and stable operation of power grids [1]. By simulating the inertia, damping, frequency regulation and voltage regulation characteristics of synchronous generators, virtual synchronous generator (VSG) control can provide effective inertia support as well as frequency and voltage support for low-inertia power systems and has become a mainstream control scheme for new energy grid integration, microgrids and grid-forming converters. Nevertheless, under practical operating conditions including a weak grid, high resistance-to-reactance ratio and large power angle, strong cross-coupling exists between the active and reactive power control loops of VSGs [2]. This not only causes steady-state errors and distorted dynamic responses of reactive power but also exacerbates frequency and voltage oscillations, restricts power transmission capacity, and even triggers system instability. Recent studies have indicated that coupling interactions may become a dominant source of instability in power-electronic-based energy conversion systems under weak grid conditions. In particular, an analysis of coupling dissipativity has revealed that severe coupling dynamics rather than local subsystem dynamics can trigger oscillatory instability, highlighting the importance of coupling suppression for system stability enhancement [3]. Therefore, realizing the efficient power decoupling of VSGs under complex operating conditions and collaboratively improving inertia–damping support and dynamic stability have become critical problems to be solved urgently.

To address the problems of the power oscillation and frequency stability of VSGs, scholars have conducted extensive studies on adaptive virtual inertia and damping control. Ref. [4] proposes a distributed adaptive virtual inertia control strategy for multiple grid-connected VSGs, which adjusts inertia adaptively according to the deviation between local frequency and regional average frequency to suppress power oscillations and optimize frequency dynamic responses, yet it ignores the influence of power coupling on control performance. Ref. [5] applies adaptive virtual inertia to the VSG control of AC microgrids, which increases inertia during frequency deviation and reduces inertia during frequency recovery to balance frequency support and rapid convergence while lacking the design of active–reactive power decoupling. In [6], a data-driven-based optimal virtual inertia control strategy for VSGs is designed to enhance the suppression effect on frequency drop and the rate of frequency change, but the cross-power coupling issue remains unresolved. Ref. [7] presents a multi-objective adaptive inertia–droop control strategy for wind turbines, which realizes coordinated frequency support and speed recovery and is suitable for scenarios with high wind power penetration, yet it cannot be directly applied to VSG power decoupling. Ref. [8] establishes an adaptive virtual inertia–damping system based on model predictive control (MPC) to improve the frequency stability of low-inertia microgrids, without dedicated decoupling design for power coupling. Ref. [9] combines virtual inertia with additional damping controllers to suppress the oscillations of wind power grid-connected systems, which also fails to eliminate coupling among power loops. Ref. [10] proposes fuzzy adaptive virtual inertia for doubly fed induction generators to improve frequency regulation capability, without involving VSG power decoupling and coordinated control.

To solve the power coupling problem of VSGs, existing studies have focused on in-depth investigations of power decoupling control methods. Ref. [11] proposes a full-state feedback power decoupling strategy for VSGs, where the state feedback matrix is designed to eliminate active–reactive power coupling while retaining inertia response capability. Disturbance injection is further introduced to reduce dependence on line parameters and

improve system stability. However, the method mainly relies on state feedback decoupling design and does not incorporate adaptive inertia–damping optimization under varying operating conditions. Ref. [12] proposes a frequency and amplitude feedforward decoupling strategy for grid-forming converters to realize decoupling between active and reactive power control loops, which features a simple principle and easy implementation but fails to consider operating conditions with large power angles and weak grids. Ref. [13] presents a VSG power decoupling method based on online adaptive feedforward compensation (OAFC) for weak grids, which can adapt to time-varying line impedance and variable operating points, yet it is not coordinated with inertia and damping control. Ref. [14] comprehensively reviews and classifies active power decoupling (APD) control strategies, providing theoretical references for power ripple suppression in single-phase systems. Ref. [15] puts forward a dynamic power decoupling method for grid-forming converters under strong grids to restrain dynamic interaction between active and reactive power, whereas its applicable scenarios are limited. Ref. [16] establishes hierarchical adaptive decoupling control (HADC) for wind farms connected to weak grids, which suppresses the power coupling caused by phase-locked loop and grid strength and improves grid-friendliness. In the field of power decoupling, Refs. [17,18] respectively propose common-ground and reduced-switch active power decoupling topologies for photovoltaic inverters to reduce leakage current and second-order power ripple. Refs. [19,20] achieve the decoupled power control of photovoltaic systems via model predictive control to accelerate dynamic response. Ref. [21] realizes second-order harmonic active decoupling for differential boost inverters. Refs. [22,23] propose dual synchronous coordinate decoupling and phase-locked loop-free decoupling strategies for multi-source inverters and marine propulsion systems respectively. Although the above methods have achieved favorable effects in power decoupling and harmonic suppression, most of them focus on topology design, single-phase systems or specific types of converters and cannot be directly applied to satisfy the coordinated control requirements of inertia, damping and decoupling for VSGs under the conditions of a weak grid and large power angle [24]. In general, existing decoupling strategies either are only applicable to small-power-angle scenarios or operate independently from inertia and damping control, making it difficult to simultaneously achieve the comprehensive goals of decoupling, frequency stabilization and oscillation suppression under complex operating conditions.

To this end, this paper proposes a VSG control strategy based on reactive power feedforward decoupling and coordinated adaptive damping–inertia regulation. First, a quantitative coupling analysis based on small-signal modeling and a dynamic relative gain array (DRGA) is conducted to reveal the influence of large-power-angle and high- R/X conditions on active–reactive power coupling. Based on this analysis, a reactive-power-oriented feedforward decoupling strategy is designed to suppress Q – θ coupling while preserving the intrinsic inertia support characteristics of the active power loop. Furthermore, a deep deterministic policy gradient (DDPG)-based adaptive damping–inertia control method is developed, where frequency, voltage, power, and coupling degree are incorporated into the state space to achieve the online coordinated optimization of virtual inertia and damping. Compared with existing decoupling or adaptive control methods, the proposed approach simultaneously achieves effective power decoupling, enhanced inertia support, improved oscillation suppression, and strong robustness against parameter uncertainty, thereby significantly improving the dynamic performance and grid-connected stability of VSGs under weak grid and high- R/X operating conditions.

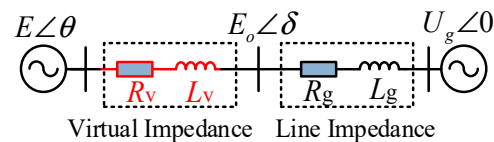


Figure 2. Equivalent circuit diagram of grid-connected VSG.

Let $Z_{\text{sum}}\angle\alpha = R_g + R_v + j\omega_n L_g + j\omega_n L_v$, $R_{\text{sum}} = R_g + R_v$, and $L_{\text{sum}} = L_g + L_v$; it is known that the output power of the VSG can be expressed as follows:

$$\begin{cases} P_e = \frac{3E}{Z_{\text{sum}}} [E \cos \alpha - U_g \cos(\theta + \alpha)] \\ Q_e = \frac{3E}{Z_{\text{sum}}} [E \sin \alpha - U_g \sin(\theta + \alpha)] \end{cases} \quad (4)$$

The partial derivatives of P_e and Q_e with respect to E and θ can be derived as follows:

$$\begin{cases} G_{11} = \frac{dP_e}{d\theta} = \frac{EU_g}{Z_{\text{sum}}} \sin(\theta + \alpha) \\ G_{12} = \frac{dP_e}{dE} = \frac{1}{Z_{\text{sum}}} [2E \cos \alpha - U_g \cos(\theta + \alpha)] \\ G_{21} = \frac{dQ_e}{d\theta} = -\frac{EU_g}{Z_{\text{sum}}} \cos(\theta + \alpha) \\ G_{22} = \frac{dQ_e}{dE} = \frac{1}{Z_{\text{sum}}} [2E \sin \alpha - U_g \sin(\theta + \alpha)] \end{cases} \quad (5)$$

To reveal the power coupling relationship, take θ as the independent variable and G_{11} , G_{12} , G_{21} and G_{22} as dependent variables. The corresponding relationship curves are shown in Figure 3.

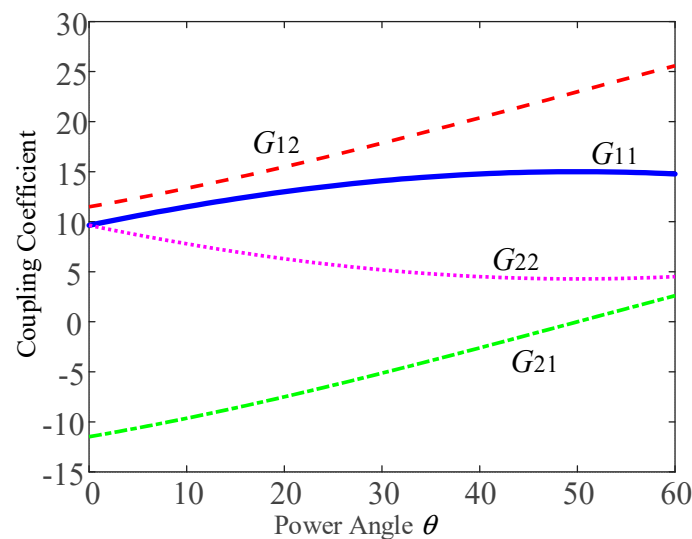


Figure 3. Variation curves of G_{11} , G_{12} , G_{21} and G_{22} with power angle.

It can be observed from Figure 3 that G_{12} rises approximately linearly with the increase in power angle, indicating that the control effect of excitation voltage on active power is continuously strengthened. As the power angle increases, G_{21} gradually approaches zero from negative values, which means that both the magnitude and polarity of the influence exerted by power angle on reactive power change. The above variation laws reveal that the cross-coupling effect of θ and E on P_e and Q_e is markedly intensified as the power angle rises. The ideal decoupling characteristic that active power is regulated by θ and reactive power by E is severely destroyed. In extreme cases, the control strength of excitation voltage on active power even exceeds that of power angle.

Considering the dynamic process of the system, a wide-frequency-domain dynamic small-signal model of the system integrated with a virtual synchronous generator is es-

tablished. The expressions of active power and reactive power are presented in Equation (6).

$$\begin{cases} P = \frac{(R_g + sL_g)(E^2 - EU_g \cos \theta) + X_g EU_g \sin \theta}{(R_g + sL_g)^2 + X_g^2} \\ Q = \frac{X_g(E^2 - EU_g \cos \theta) - (R_g + sL_g)EU_g \sin \theta}{(R_g + sL_g)^2 + X_g^2} \end{cases} \quad (6)$$

Linearizing Equation (6) at the steady-state operating point yields the small-signal model of power as follows:

$$\begin{bmatrix} \Delta P(s) \\ \Delta Q(s) \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{\partial \Delta P(s)}{\partial \Delta \theta(s)} & \frac{\partial \Delta P(s)}{\partial \Delta E(s)} \\ \frac{\partial \Delta Q(s)}{\partial \Delta \theta(s)} & \frac{\partial \Delta Q(s)}{\partial \Delta E(s)} \end{bmatrix}}_{G(s)} \begin{bmatrix} \Delta \theta(s) \\ \Delta E(s) \end{bmatrix} = \begin{bmatrix} G_{P\theta}(s) & G_{PE}(s) \\ G_{Q\theta}(s) & G_{QE}(s) \end{bmatrix} \begin{bmatrix} \Delta \theta(s) \\ \Delta E(s) \end{bmatrix} \quad (7)$$

It can be seen from Figure 4 that obvious active–reactive power coupling exists in VSG control. When active power disturbance occurs, it will not only trigger the regulation process of the active power control loop but also affect the output of reactive power via cross-coupling terms. Conversely, variations in reactive power will in turn interfere with the dynamic response of active power. Such mutual interaction between control loops causes power fluctuations to propagate mutually, prolongs system regulation time and increases the amplitude of power oscillation during transients. In the case of insufficient system damping, the coupling effect may even induce sustained frequency and power oscillations, which seriously endangers system stability. This coupling phenomenon deteriorates the stability of the VSG control system. Therefore, it is essential to investigate effective decoupling control strategies to address the power coupling issue caused by increasing power angles.

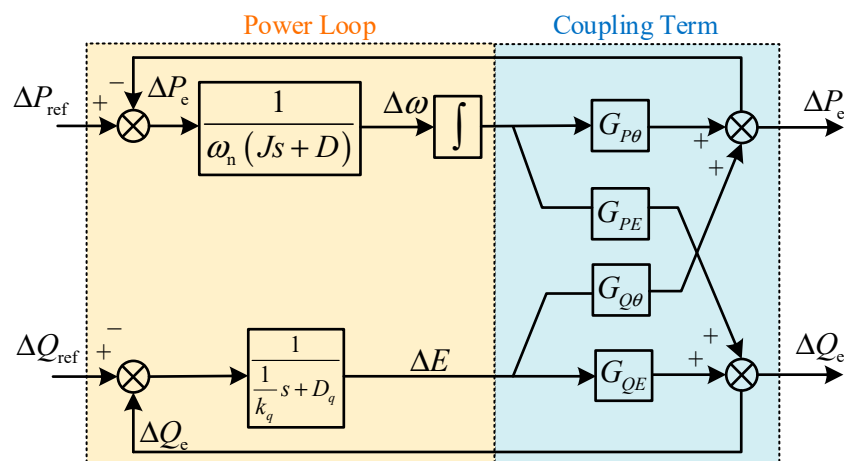


Figure 4. Small-signal control block diagram of VSG control.

To quantitatively evaluate the coupling degree of multi-input multi-output systems, the dynamic relative gain array (DRGA) is commonly adopted for analysis, and the corresponding DRGA is expressed as follows:

$$\Lambda(s) = G(s) \otimes \left(G^{-1}(s) \right)^T \quad (8)$$

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \quad (9)$$

$$\text{where } \lambda_{11} = \frac{G_{P\theta}(s)G_{QE}(s)}{G_{P\theta}(s)G_{QE}(s) - G_{PE}(s)G_{Q\theta}(s)}.$$

The value of λ_{11} directly reflects the system's coupling degree. When $|\lambda_{11}|$ is close to 1, system coupling can be neglected. When $|\lambda_{11}|$ is less than 0.5, severe system coupling occurs, and decoupling design is required. In addition, the smaller the magnitude of $|\lambda_{11}|$, the stronger the system coupling.

It can be seen from Figures 5 and 6 that the value of $|\lambda_{11}|$ varies with frequency, indicating that the system coupling degree differs in different frequency bands during dynamic operation. Since the studied frequency range is limited within the control bandwidth, high-frequency bands are excluded from the following analysis. In the low-frequency band, large power angles and high impedance ratios will aggravate system coupling. In the mid-frequency band, $|\lambda_{11}|$ continues to change with frequency and presents resonant peaks, whose magnitudes are affected by power angles and impedance ratios and are obviously higher than those in the low-frequency band.

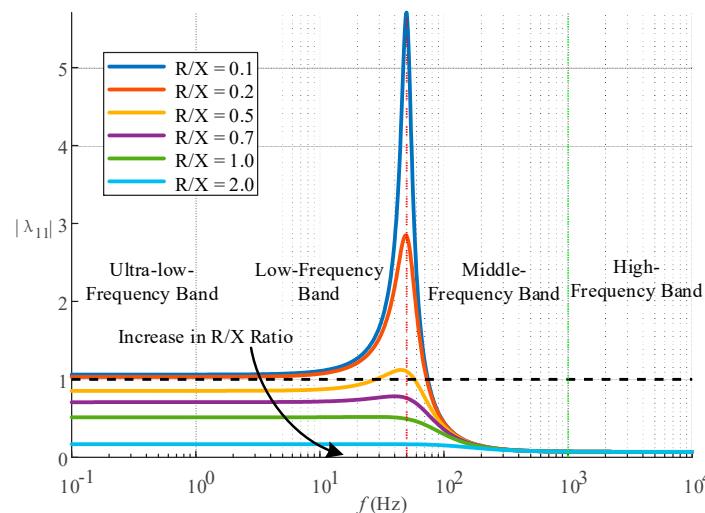


Figure 5. Variation curve of coefficient $|\lambda_{11}|$ with different R/X ratios.

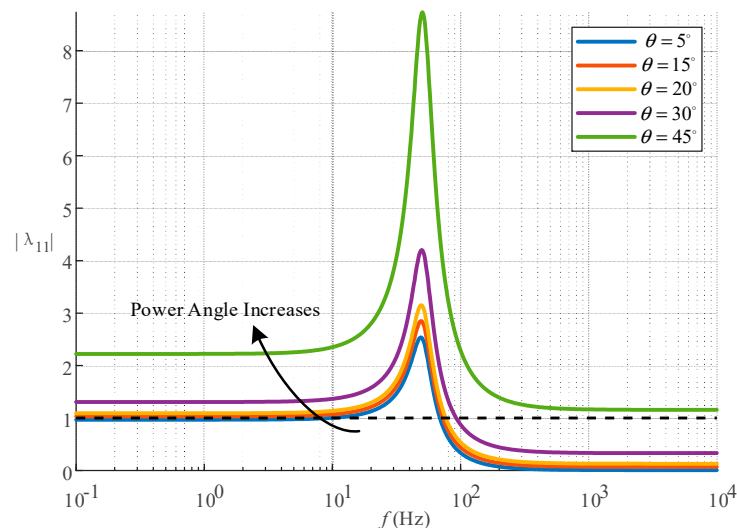


Figure 6. Variation curve of coefficient $|\lambda_{11}|$ with power angle.

Under the operating conditions of a weak grid, large power angle and high impedance ratio, the low-frequency coupling effect of the VSG system is intensified, and the coupling characteristics in other frequency bands are also altered. If the decoupling strategy is designed merely based on steady-state gains while ignoring the dynamic variation process of the system, satisfactory decoupling performance cannot be achieved. Therefore, it is highly necessary to introduce dynamic decoupling control.

3. Power Feedforward Decoupling

Considering that the active power loop is closely linked with the VSG swing equation, its dynamic characteristics directly determine the inertial support capability and frequency stability of the system. Strong decoupling compensation applied to the active loop can suppress power coupling, yet it may weaken the inherent synchronous generator characteristics, reduce system damping and dynamic stability, and even trigger frequency oscillations under weak grid and large-power-angle operating conditions. For this reason, this paper retains the original inertial response mechanism of the active power loop and only adopts directional feedforward decoupling for the reactive power loop to weaken the cross-coupling between reactive power and power angle so as to optimize the dynamic performance of reactive power and grid voltage. Meanwhile, to improve the poor dynamic adaptability of the active power loop, the adaptive damping and inertia control based on the DDPG is further introduced to realize the coordinated optimization of system stability and dynamic response performance.

The power deviation caused by the power angle is corrected using $G_{\theta v} \int (\omega_0 - \omega) dt$, $\Delta\theta = \int (\omega_0 - \omega) dt$. Combined with the equation $\omega = d\theta/dt$, the reactive power feedforward link can be expressed as follows:

$$Q_{\text{ref}} - Q_e + \frac{1}{k_q}(E_{\text{ref}} - E) - G_{\theta v} \int (\omega_0 - \omega) dt = J_q \frac{dE}{dt} \quad (10)$$

$$Q_{\text{ff}} = G_{\theta v} \int (\omega_0 - \omega) dt \quad (11)$$

The reactive power control loop with power feedforward decoupling is shown in Figure 7.

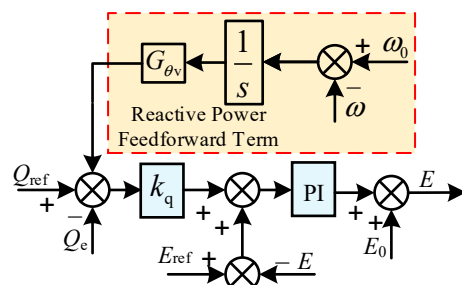


Figure 7. Reactive power control loop with power feedforward decoupling.

When the VSG operates at steady state, the output reactive power of the VSG is as follows:

$$Q_{e0} = \frac{E_0}{Z_{\text{sum}}} [E_0 \sin \alpha - U_g \sin(\theta + \alpha)] \quad (12)$$

The power angle of the VSG becomes θ_f after system disturbance, where $\theta_f = \theta + \Delta\theta$, and the corresponding output reactive power is as follows:

$$\begin{aligned} Q_{ef} &= \frac{E_f^2}{Z_{\text{sum}}} \sin \alpha - \frac{E_f U_g}{Z_{\text{sum}}} \sin(\theta + \alpha + \Delta\theta) \\ &= \frac{E_f^2}{Z_{\text{sum}}} \sin \alpha - \frac{E_f U_g}{Z_{\text{sum}}} (\sin(\theta + \alpha) + \cos(\theta + \alpha) \Delta\theta) \end{aligned} \quad (13)$$

$$\Delta Q = Q_{e0} - Q_{ef} \quad (14)$$

ΔQ contains steady-state terms and transient deviations. To eliminate reactive power deviation, the power control term Q_v is added to the reactive power loop.

$$Q_v = G_{\theta v} \Delta\theta = \frac{E_f U_g}{Z_{\text{sum}}} \cos(\theta + \alpha) \Delta\theta \quad (15)$$

$$G_{\theta v} = \frac{E_f U_g}{Z_{\text{sum}}} \cos(\theta + \alpha) \quad (16)$$

To further verify the influence of different decoupling strategies on system stability, eigenvalue migration analysis is carried out based on the established small-signal model.

To quantitatively analyze the effect of different decoupling strategies on system stability, this paper further investigates the migration law of closed-loop eigenvalues when the virtual inertia J varies from 1 to 40, and the results are depicted in Figure 8. At $J = 10$, the dominant poles of the reactive power decoupling scheme are $-1.79 \pm j4.46$, while those of the full PQ decoupling scheme are $-1.24 \pm j6.51$. The damping ratio of the proposed reactive power decoupling strategy is 0.372, in contrast to 0.187 for the full PQ decoupling method. The reactive-power-only decoupling strategy achieves a higher damping ratio and superior stability. All eigenvalues under both control schemes lie in the left half of the complex plane, which guarantees stable system operation. As the virtual inertia increases, the dominant conjugate complex poles gradually shift toward the imaginary axis, indicating reduced oscillation frequency and degraded system damping. Compared with the full active–reactive power decoupling strategy, the dominant poles of the reactive-power-only decoupling strategy always stay further left with larger negative real parts and higher damping, which confirms the larger stability margin of the proposed scheme.

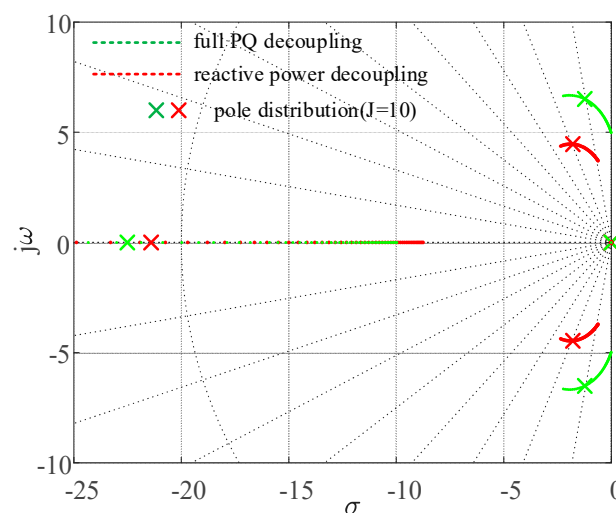


Figure 8. Pole migration comparison between reactive power decoupling and full PQ decoupling as J varies from 1 to 40.

4. Adaptive Damping and Inertia Control

To enhance the adaptive capability of the VSG against variations in operating conditions, this paper introduces the deep reinforcement learning algorithm DDPG to construct a cooperative adaptive damping and inertia control method. By perceiving the real-time dynamic state of the system, the proposed method autonomously adjusts the virtual inertia and damping parameters, thereby optimizing the system's dynamic performance and suppressing oscillations.

4.1. Principle of DDPG Algorithm

The DDPG is a deep reinforcement learning algorithm based on the Actor–Critic framework, which is applicable to control problems with continuous action spaces. Its core idea is that the agent continuously interacts with the environment, outputs control actions according to the system's operating state, and updates the control strategy in real time based on the reward function to obtain the optimal control effect.

The DDPG mainly consists of four components: an online Actor network, online Critic network, target Actor network and target Critic network. Specifically, the Actor network outputs control actions according to the current system state; the Critic network evaluates the quality of the executed actions; the target networks are adopted to improve training stability; and the experience replay mechanism is used to reduce sample correlation.

The basic control process is shown in Figure 9.

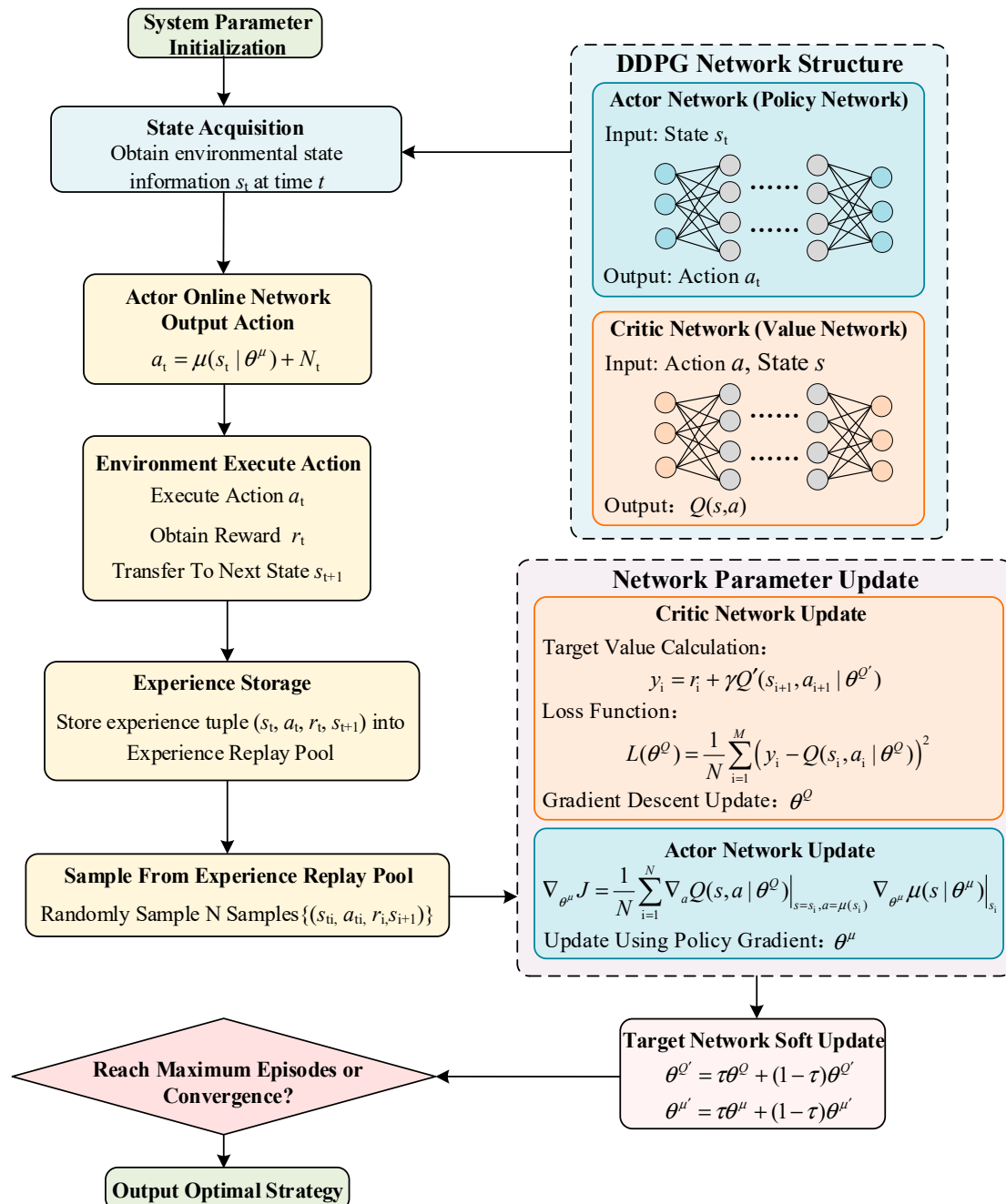


Figure 9. Basic control flow diagram of DDPG algorithm.

First, the agent collects the environmental state information s_t at the current time step t and feeds it into the online Actor network μ . The online Actor network then obtains the current action a_t based on its current network parameters θ^μ and random noise N_t . The corresponding formula is as follows:

$$a_t = \mu(s_t | \theta^\mu) + N_t \quad (17)$$

where $\mu(s_t|\theta^\mu)$ denotes the action output by the Actor network; N_t is the random exploration noise.

After the environment executes the action, it obtains the reward value r_t and transitions to the next state s_{t+1} . Upon acquiring the current environmental state s_t and the action a_t , the reward r_t is calculated, and the environment then proceeds to the next state s_{t+1} . To fully utilize the experience to accelerate network training, the experience tuple (s_t, a_t, r_t, s_{t+1}) is stored in the experience replay buffer.

The Critic network evaluates the current action benefit through the action-value function $Q(s,a): Q(s_t, a_t|\theta^Q)$. θ^Q is the parameter of the Critic network.

Assume that the number of experiences sampled each time is M . The training of the Critic network is similar to that of supervised learning, and the formula for minimizing the loss function is as follows:

$$L(\theta^Q) = \frac{1}{N} \sum_{i=1}^M \left(y_i - Q(s_i, a_i | \theta^Q) \right)^2 \quad (18)$$

The target value y_i is given by the following:

$$y_i = r_i + \gamma Q'(s_{i+1}, a_{i+1} | \theta^{Q'}) \quad (19)$$

where γ is the discount factor; Q' is the target Critic network.

The Actor network is updated via the policy gradient:

$$\nabla_{\theta^\mu} J = \frac{1}{N} \sum_{i=1}^N \nabla_a Q(s, a | \theta^Q) \Big|_{s=s_i, a=\mu(s_i)} \nabla_{\theta^\mu} \mu(s | \theta^\mu) \Big|_{s_i} \quad (20)$$

where N is the total number of time steps in one episode.

Finally, the agent updates the target Actor and target Critic networks with a tiny update rate τ . The corresponding update formulas are as follows:

$$\begin{aligned} \theta^{Q'} &= \tau \theta^Q + (1 - \tau) \theta^{Q'} \\ \theta^{\mu'} &= \tau \theta^\mu + (1 - \tau) \theta^{\mu'} \end{aligned} \quad (21)$$

Through continuous iterative training, the DDPG agent can learn the optimal adjustment strategy of damping and inertia parameters under different operating conditions.

4.2. Implementation of Adaptive Damping and Inertia Control

To enable the agent to accurately perceive the dynamic characteristics of the system, this paper selects variables such as frequency, voltage, power and coupling state to construct the state space. The system state variables are defined as follows:

$$s = [\Delta f, \dot{\Delta f}, \Delta P, \Delta Q, \Delta U, \theta, m] \quad (22)$$

where Δf denotes frequency deviation; $\dot{\Delta f}$ represents the rate of change of frequency (RoCoF); ΔP is active power deviation; ΔQ is reactive power deviation; ΔU stands for voltage deviation; θ is power angle variation; $m = |\lambda_{11} - 1|$ is the power coupling index.

The power coupling index is used to characterize the degree of dynamic coupling in the system. As system coupling increases, $m = |\lambda_{11} - 1|$ will increase significantly. Therefore, introducing it into the state space enables the agent to perceive the coupling status, thereby improving its dynamic adaptability under complex operating conditions.

The action output by the DDPG agent is the virtual inertia and damping parameters of the VSG, i.e.,

$$a = [J, D] \quad (23)$$

where J denotes the virtual inertia; D represents the virtual damping coefficient.

To ensure the operational stability of the system, constraint ranges are set for the action space:

$$J_{\min} \leq J \leq J_{\max} \quad (24)$$

$$D_{\min} \leq D \leq D_{\max} \quad (25)$$

When the inertia and damping coefficients satisfy the aforementioned constraint ranges, the real parts of the dominant closed-loop eigenvalues remain negative, guaranteeing the asymptotic stability of the closed-loop system. Accordingly, the aforementioned stability region is adopted in this paper as the action space constraint for the DDPG algorithm, which restricts the online optimization of the agent strictly within the stability domain and thus prevents the generation of unstable control parameters.

By dynamically adjusting J and D online, the system can autonomously change its inertia support capability and damping level according to different operating conditions, thus achieving the optimization of dynamic performance.

The reward function determines the optimization objective of reinforcement learning, and its design directly affects the training effect of the agent. To comprehensively improve the system's frequency stability, dynamic response capability, and power coupling suppression capability, this paper constructs the following reward function:

$$r = -w_1(\Delta f)^2 - w_2(\Delta U)^2 - w_3(\Delta P)^2 - w_4(\Delta Q)^2 - w_5 m - w_6 T_s \quad (26)$$

where $w_1 \sim w_6$ are the weight coefficients of each performance index. The weighting coefficients are set as $w_1 = 2$, $w_2 = 1$, $w_3 = 1.5$, $w_4 = 1$, $w_5 = 2$, and $w_6 = 1$. The larger values of w_1 and w_5 are adopted to enhance frequency stability and the suppression capability of power coupling; w_3 is configured to damp active power oscillations; w_2 and w_4 are used to balance the dynamic performance of voltage and reactive power; and w_6 is designed to shorten the dynamic settling time of the system. T_s denotes the dynamic regulation time of the system.

The design of the multi-objective reward function realizes the collaborative optimization of frequency stability, voltage stability and coupling suppression.

4.3. Training Environment and Parameter Settings of DDPG

To improve the repeatability and generalization capability of the proposed adaptive damping and inertia control strategy, the training environment and network hyperparameters of the DDPG agent are uniformly configured in this paper. Both the Actor and Critic networks adopt fully connected feedforward neural networks. The Actor network consists of two hidden layers with 128 and 64 neurons respectively; the rectified linear unit (ReLU) is selected as the activation function, and the tanh function is used at the output layer to constrain the output range of control actions. The Critic network takes the concatenated state–action pair as its input, with two hidden layers also configured with 128 and 64 neurons.

During training, the capacity of the experience replay buffer is set to 1×10^6 , and the mini-batch size M is fixed at 256. The discount factor γ is specified as 0.99 to balance long-term dynamic performance, and the soft-update coefficient τ for target networks is set to 0.005 to enhance training stability. The learning rates of the Actor and Critic networks are 1×10^{-4} and 5×10^{-4} , respectively. The Ornstein–Uhlenbeck stochastic noise is adopted

as the exploration strategy, whose initial standard deviation is initialized to 0.2 and decays gradually along with training episodes.

To strengthen the agent's adaptability against complicated operating conditions, grid parameters and disturbance scenarios are randomly varied throughout the training process. Specifically, the line resistance-to-inductance ratio R/X ranges from 0.1 to 1, the short-circuit ratio (SCR) varies between 2 and 10, the steady-state power angle is limited within 10° – 45° , the amplitude of frequency disturbance is constrained to ± 0.5 Hz, and active power step disturbance is set from 0.2 to 0.5 p.u. Each training episode contains 1000 control time steps, and the total number of training episodes is 3000. The training is regarded as converged if the variation rate of the average reward over consecutive 200 episodes is less than 5%.

Figure 10 illustrates the variation in the average reward of the DDPG agent against training episodes. To eliminate the influence of randomness, a moving average algorithm is employed to smooth the training reward curve. At the early training stage, the reward fluctuates drastically as the agent is in the random exploration phase. As training proceeds, the agent gradually learns the inertia–damping regulation strategy adaptable to diverse operating conditions, leading to a continuous rise in the average reward and a remarkable reduction in fluctuation amplitude. After approximately 1500 episodes, the reward converges to a steady value, which verifies that the DDPG agent finishes convergent training and acquires an optimal control policy.

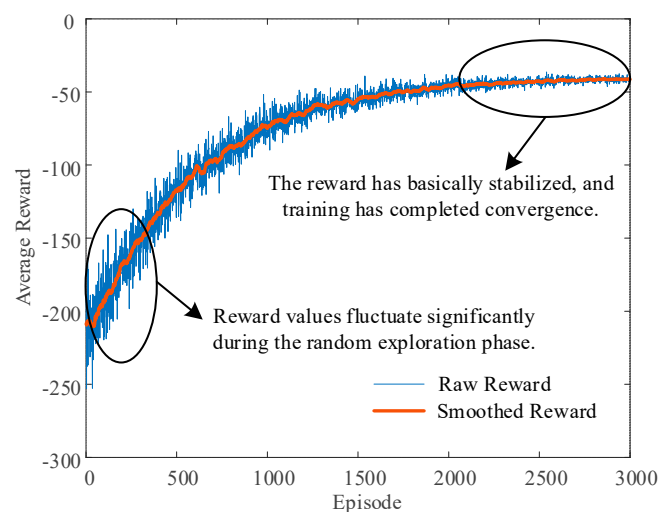


Figure 10. Reward convergence curve of DDPG agent.

Benefiting from randomized training under multiple operating scenarios, the DDPG agent can learn the optimal coordinated inertia–damping regulation strategy corresponding to various grid strengths and operating states, improving the robustness and generalization capability of the resultant control strategy.

This paper introduces the virtual inertia and damping parameters output by the DDPG into the VSG swing equation.

$$J(t) \frac{d\omega}{dt} = P_{\text{ref}} - P_e - D(t)(\omega - \omega_0) \quad (27)$$

where $J(t)$ and $D(t)$ are the dynamic parameters output in real time by the DDPG.

When the system is disturbed, the agent increases virtual inertia to enhance inertia support capability if the rate of frequency change is large. If system oscillation intensifies, it raises the damping coefficient to strengthen oscillation suppression ability. After the system restores stability, damping and inertia are automatically reduced to improve dynamic response speed.

Therefore, this method can realize the online collaborative optimization of damping and inertia parameters according to the system's dynamic operating state and improve the dynamic stability performance of the VSG under weak grid conditions.

The overall control block diagram is shown in Figure 11.

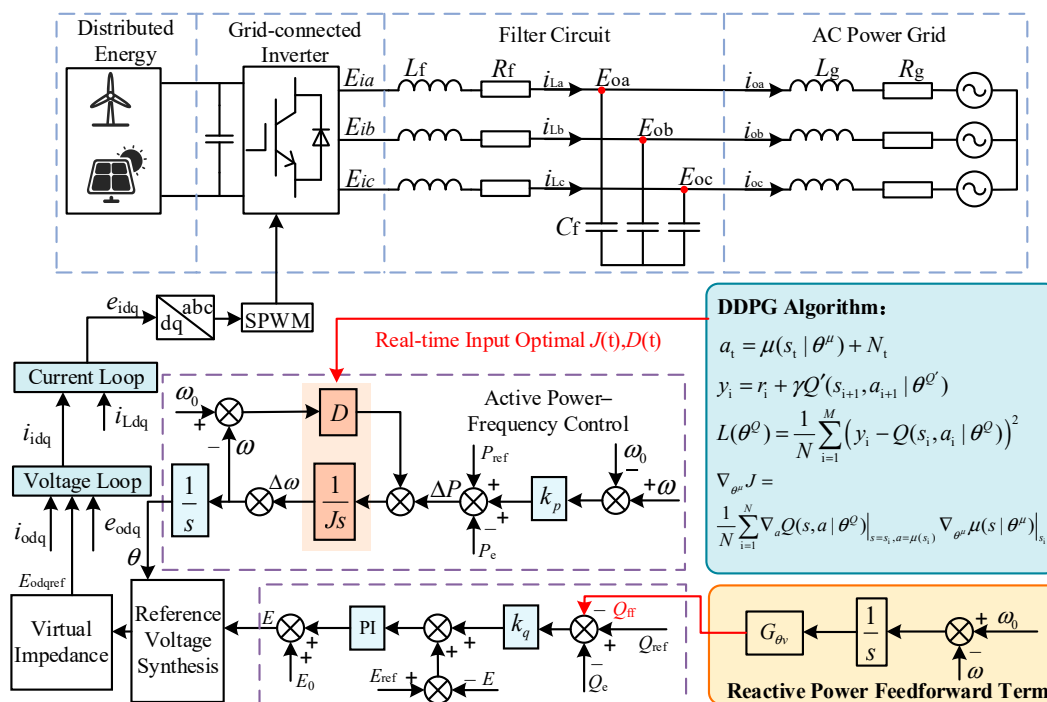


Figure 11. Block diagram of DDPG-based VSG adaptive inertia-damping control and reactive power feedforward decoupling structure.

5. Experimental Test Results

5.1. The Hardware-in-the-Loop Test Platform

A hardware-in-the-loop test platform composed of a real-time simulation machine and physical DSP controller is built, as shown in Figure 12. The main circuit of the power system is modeled and simulated on the real-time simulation device, while the proposed control strategy is programmed and operated in the physical DSP controller.

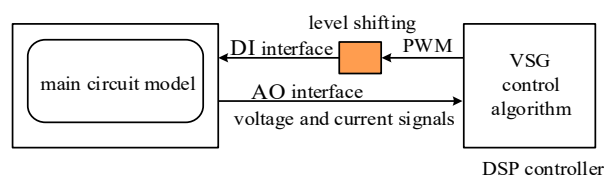


Figure 12. A schematic diagram of the built hardware-in-the-loop test platform.

To verify the effectiveness of the proposed VSG control strategy combining reactive power feedforward decoupling and adaptive inertia-damping control in theoretical analysis, algorithm design and engineering implementation and clarify its dynamic control performance and grid-connected adaptation advantages under complex operating conditions such as a weak grid, large power angle and high resistance-to-reactance ratio, comprehensive experimental verifications are carried out on the hardware-in-the-loop test platform from the perspectives of the power decoupling effect, frequency and voltage support, dynamic response speed and disturbance rejection stability. The steady-state and dynamic output characteristics of the proposed strategy are compared with those of traditional VSG control, conventional adaptive inertia control and independent power

decoupling control. The improvement effects of reactive power feedforward decoupling and DDPG-based adaptive inertia–damping control on system stability, power transmission capacity and dynamic performance are quantitatively analyzed.

Taking single-machine simulation as an example, the specific parameters are as follows (Table 1):

Table 1. VSG simulation parameters.

Model Parameters	Values	Control Parameters	Values
DC Voltage/V	600	Inertia Time Constant J	10
Switching Frequency/kHz	10	Damping Coefficient D	200
Filter Inductor/mH	1.2	Reactive Power Droop Coefficient k_q	0.4
Filter Capacitor/ μ F	30	PI Coefficients of the Voltage Loop	2, 1
Filter Internal Resistance/m Ω	0.2	PI Coefficients of the Current Loop	2, 3
Grid Voltage/V	690	Standard Angular Frequency ω_0 /(rad/s)	314.16
Control Step Size/ μ s	100	Simulation Step Size/ μ s	100

5.2. Experimental Results Under Active Power Command Variation

As shown in Figures 13 and 14, the active power command steps up from 0.5 p.u. to 1 p.u. at $t = 1$ s. All four control strategies can realize active power tracking, but their dynamic performances differ significantly.

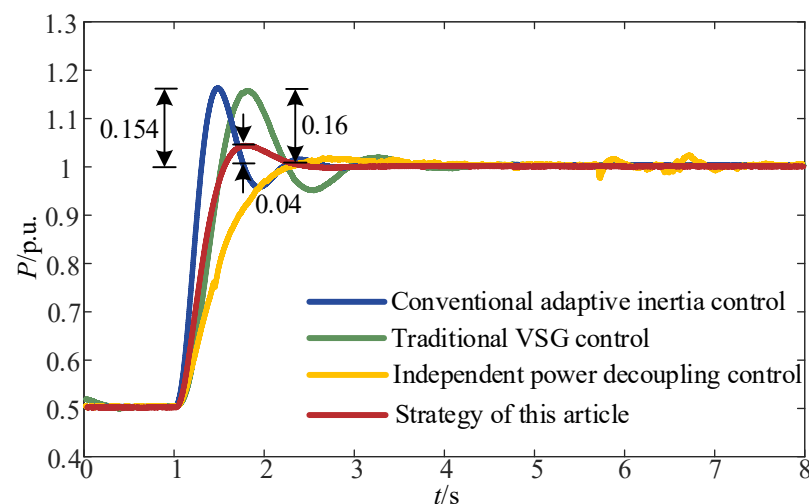


Figure 13. Comparison of active power simulation results under different control strategies.

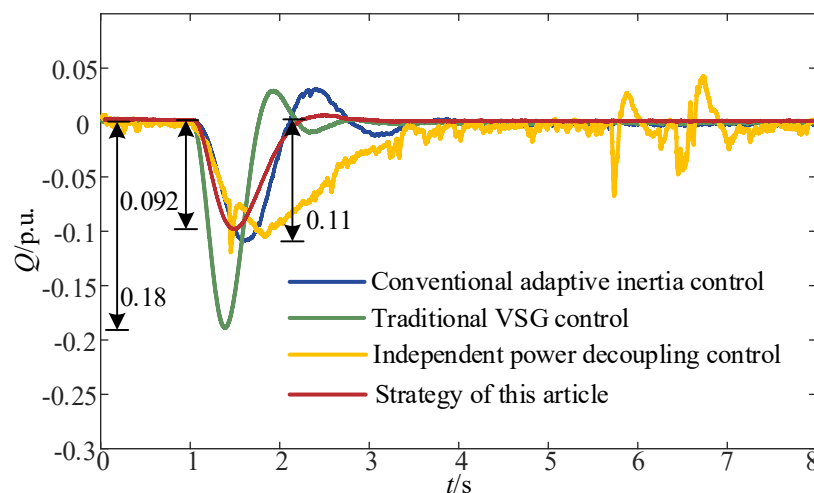


Figure 14. Comparison of reactive power simulation results under different control strategies.

It can be seen from Figure 13 that both traditional VSG control and conventional adaptive inertia control suffer from large overshoot and oscillation, with overshoots of about 0.16 p.u. and 0.154 p.u. respectively. Although independent power decoupling control weakens partial coupling effects, it features slow response speed and residual fluctuations in the later stage. In contrast, the proposed strategy has an overshoot of merely 0.04 p.u. and returns to steady state more rapidly, which verifies its superior dynamic response and oscillation suppression capability.

As illustrated in Figure 14, active power disturbances cause reactive power fluctuations under all strategies, revealing obvious active–reactive power coupling in the system. Traditional VSG control produces the maximum reactive power fluctuation of around 0.18 p.u., while the proposed strategy achieves the minimum fluctuation and fastest convergence. This proves that the adopted reactive power feedforward decoupling can effectively block the disturbance transmission from the active power loop to the reactive power loop and reduce the system's coupling degree.

In summary, the proposed strategy can improve active power dynamic performance while effectively mitigating active–reactive power coupling, thus enhancing overall system stability.

5.3. Comparison of Control Strategies Under Frequency Disturbance

As shown in Figures 15 and 16, grid frequency drops by 0.5 Hz during $t = 1 \sim 1.5$ s to verify the dynamic support capability and stability of different control strategies under frequency disturbance.

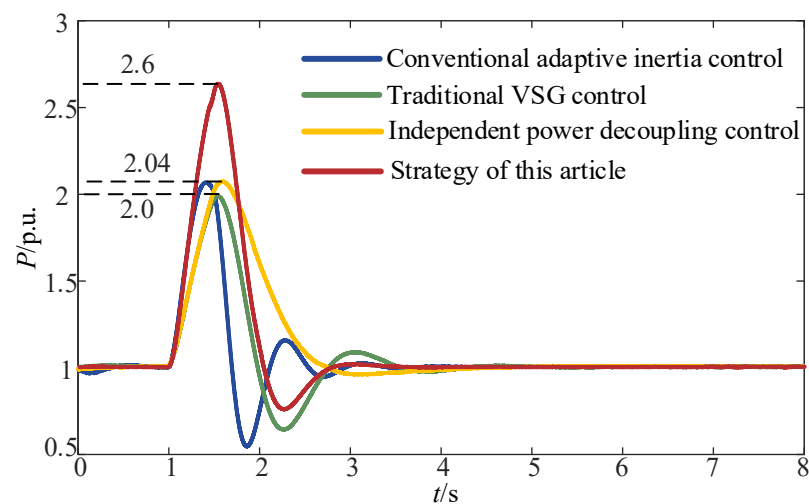


Figure 15. Active power response of system under frequency disturbance.

It can be observed from Figure 15 that all strategies adjust active power to provide inertial support after frequency disturbance occurs. Severe power oscillations exist in traditional VSG control and conventional adaptive inertia control with obvious fluctuations during dynamic recovery. Independent power decoupling control suppresses oscillations yet suffers from slow response speed. By contrast, the proposed strategy rapidly raises active power output with the maximum active support up to about 2.6 p.u., far exceeding other methods, which demonstrates stronger transient inertial support and frequency regulation capability. Meanwhile, it presents lower oscillation amplitude and faster steady-state recovery.

From Figure 16, traditional VSG control leads to the largest frequency drop and longest recovery time during grid frequency sag. Conventional adaptive inertia control and independent power decoupling control optimize frequency dynamic performance

but still have noticeable overshoot and oscillation. The proposed strategy maintains a higher minimum frequency with a recovery time of approximately 1.2 s, achieving superior performance. It proves that the presented adaptive inertia–damping control can adjust inertia and damping parameters in real time according to the system’s operating conditions, effectively strengthening system frequency support and damping characteristics.

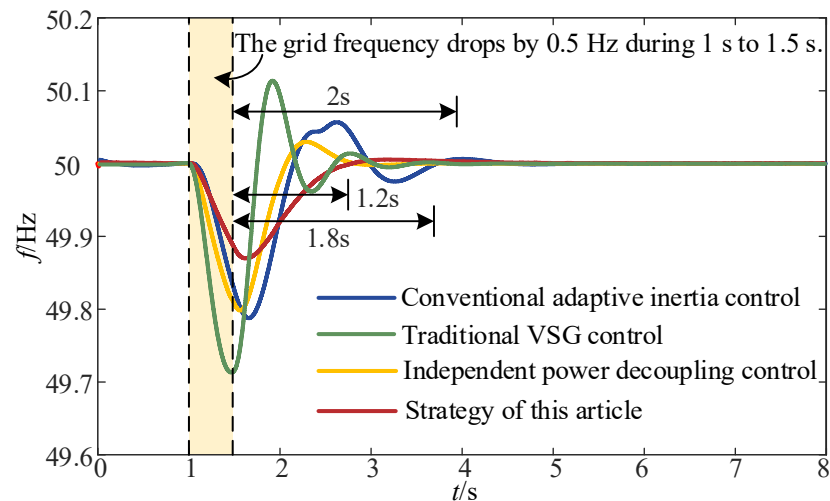


Figure 16. System frequency response under frequency disturbance.

5.4. Comparison of Strategies Under Different Short-Circuit Ratios

To verify the adaptability of the proposed strategy under different grid strengths, tests are carried out under SCR = 2 and SCR = 10, and the results are presented in Figures 17 and 18.

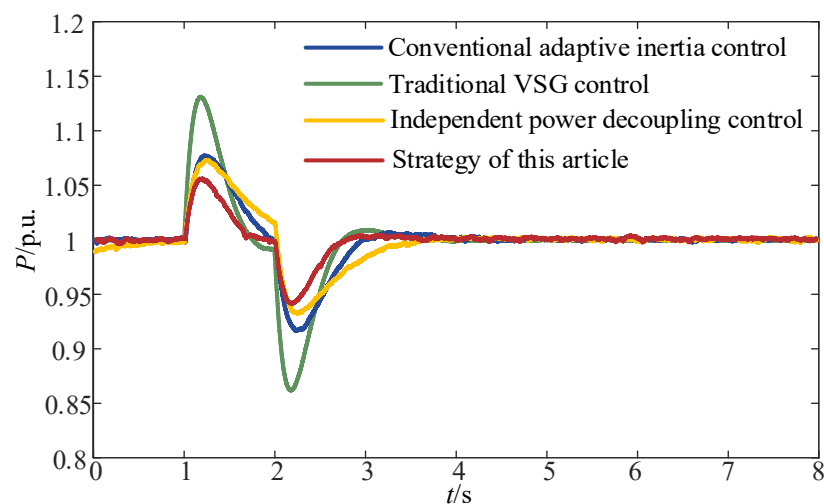


Figure 17. Active power response under transient disturbance with short-circuit ratio of 2.

Figures 17 and 18 show the active power response curves of different control strategies under transient disturbances with short-circuit ratios of 2 and 10 respectively. The comparison indicates that the traditional VSG control has the largest active power fluctuation, obvious overshoot and power drop, as well as longer dynamic recovery time. Conventional adaptive inertia control and independent power decoupling control can suppress power oscillations to a certain extent, but they still have prominent transient deviations and slow convergence. In comparison, the proposed strategy achieves the smallest overshoot and minimum power drop and can converge to steady state rapidly with nearly no obvious oscillation during transients. The results verify that the proposed method can effectively

restrain active power fluctuations and improve system transient stability and dynamic response performance under both weak and relatively strong grid conditions, which confirms the superiority and strong robustness of the adaptive inertia–damping control and reactive power feedforward decoupling scheme in complex grid environments.

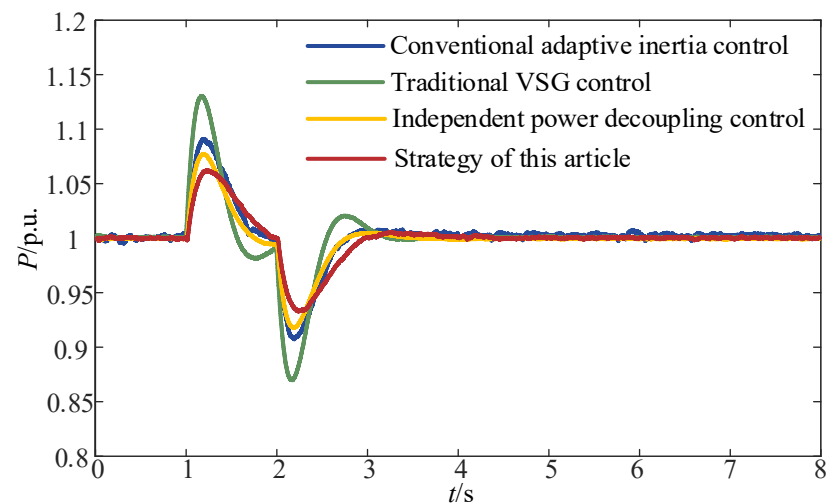


Figure 18. Active power response under transient disturbance with short-circuit ratio of 10.

5.5. Sensitivity Analysis of Impedance Estimation Error

To evaluate the robustness of the proposed feedforward decoupling control strategy against grid impedance uncertainty, this section conducts a sensitivity analysis on the estimation error of total grid impedance Z_{sum} . In practical power systems, Z_{sum} cannot be measured accurately. Restricted by changes in network topologies and estimation methods, deviations will exist between the estimated value adopted in the controller and the true value.

Define the estimated impedance used in the controller as follows: $Z_{\text{sum,est}} = kZ_{\text{sum}}$.

Here, k denotes the scaling coefficient and represents the estimation error. Five typical operating conditions with $k = 0.5, 0.8, 1.0, 1.2, 1.5$ are selected in this paper, corresponding to impedance estimation errors of -50% , -20% , 0% , $+20\%$ and $+50\%$ respectively.

The key performance indicators of the system are compared under different error conditions, as shown in Figures 19 and 20.

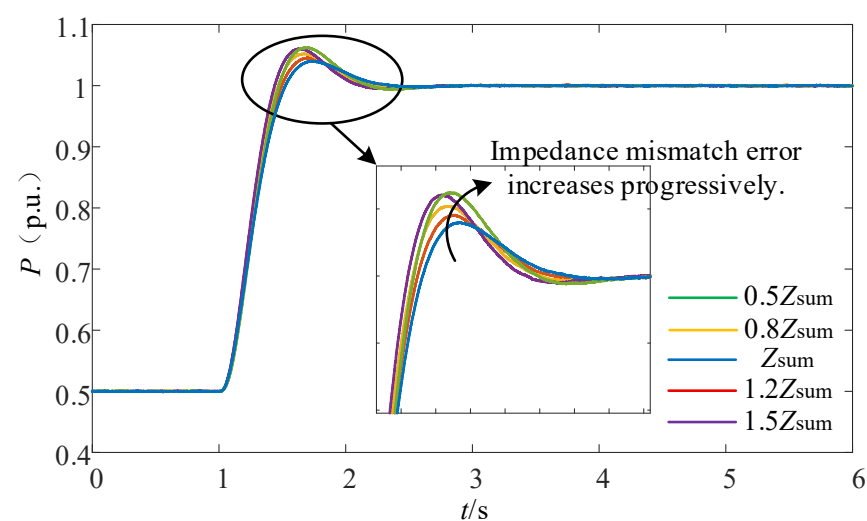


Figure 19. Active power response curves under different impedance estimation errors.

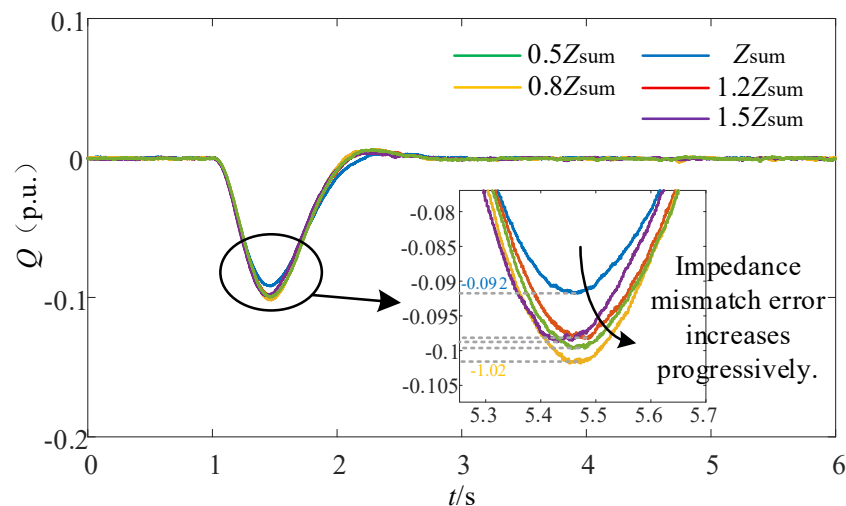


Figure 20. Reactive power response curves under different impedance estimation errors.

Figures 19 and 20 present the active and reactive power responses with grid impedance estimation errors of $\pm 50\%$ and $\pm 20\%$. Under all operating conditions, active power can be tracked stably, and the fluctuation amplitude of reactive power is limited within 0.11 p.u. with rapid convergence. The results verify the strong robustness of the proposed strategy against impedance uncertainty.

5.6. Composite Disturbance Conditions

Combined with the actual operating characteristics of weak grids, a composite disturbance scenario consisting of active power step change and grid frequency drop is established. At $t = 1$ s, the active power reference steps up from 0.5 p.u. to 1.0 p.u., and grid frequency drops by 0.2 Hz simultaneously. This setup simulates the typical complex operating conditions where the on-site converter is subjected to sudden power variation and frequency disturbance concurrently.

Figure 21 shows the active power response curve under the composite disturbance of active power step change and grid frequency drop. The comparison results indicate that the overshoot of active power under traditional VSG control reaches 15.6%, while that of the proposed strategy is only 7%. The proposed strategy features smaller dynamic fluctuations and faster recovery speed, which effectively suppresses the impact of composite disturbance on active power.

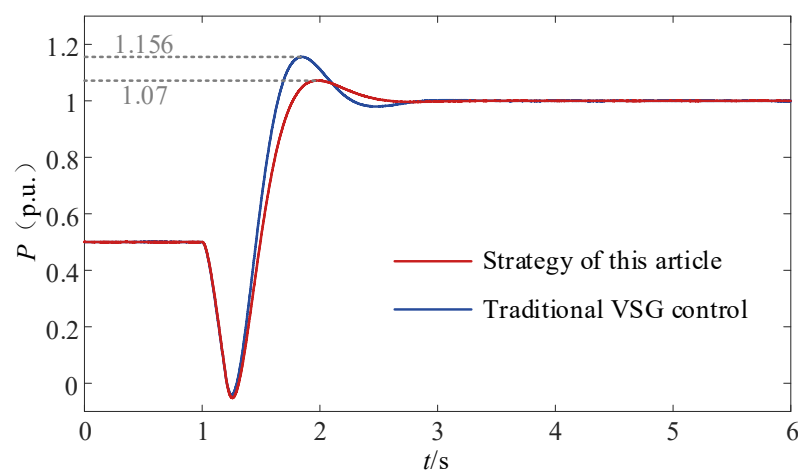


Figure 21. Active power response curves under composite disturbance of active power step change and grid frequency drop.

6. Conclusions

This paper proposes a cooperative control strategy integrating reactive power feedforward decoupling and DDPG-based adaptive damping–inertia regulation to address the severe active–reactive power coupling and insufficient dynamic adaptability of virtual synchronous generators under the operating conditions of a weak grid, high resistance-to-reactance ratio, and large power angle. The main conclusions are as follows.

- (1) Based on the established small-signal model and DRGA analysis, the coupling mechanism of VSGs is quantitatively revealed. The results show that large power angles and high resistance-to-reactance ratios significantly aggravate active–reactive power coupling, especially in the low-frequency range, thereby degrading dynamic performance and system stability.
- (2) A reactive-power-oriented feedforward decoupling strategy is developed to suppress Q – θ coupling while preserving the intrinsic inertia support characteristics of the active power loop. Combined with the DDPG-based adaptive damping–inertia controller, the proposed method achieves the online coordinated optimization of virtual inertia and damping. Eigenvalue analysis further demonstrates that the proposed decoupling strategy provides higher damping and larger stability margins than conventional full active–reactive power decoupling.
- (3) The hardware-in-the-loop results verify that the proposed strategy effectively reduces power overshoot and oscillation, improves frequency support and dynamic response, and suppresses active–reactive power coupling under various operating conditions. Moreover, satisfactory performance is maintained under grid impedance estimation errors and composite disturbances, demonstrating strong robustness and adaptability for practical weak grid applications.

Overall, the proposed strategy provides an effective solution for enhancing the dynamic performance, stability, and grid-connected operation of VSGs in future low-inertia power systems.

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