

# PRE-SYNCHRONIZATION CONTROL BASED ON VSG PARAMETER COOPERATIVE ADAPTATION

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**Abstract:** Virtual synchronous generator (VSG) emulate synchronous generators to provide inertia and damping support for distributed power integration. However, conventional VSG control employs fixed parameters that hinder dynamic adaptation to system changes, often resulting in grid connection impact currents and voltage harmonics. To overcome these limitations, this study proposes a pre-synchronization strategy based on coordinated adaptive control of VSG parameters. A VSG mathematical model is established to analyze parameter influences on system output characteristics. A coordinated adaptive control method incorporating rotational inertia and damping coefficients is then developed, which demonstrates faster suppression of excessive changes and deviations in output response compared to conventional strategies. Furthermore, a pre-synchronization mechanism is integrated to achieve smooth grid synchronization while significantly reducing inrush currents and voltage harmonics before and after connection. Simulation results via PSCAD validate the feasibility and effectiveness of the proposed control strategy.

**Keywords:** VSG; Coordinated adaptive; Pre-synchronization

## 1 INTRODUCTION

The growing integration of distributed renewable generation—such as photovoltaic and wind power has led to an increasing share of inverter-interfaced distributed sources in microgrids. These power electronic converters inherently lack inertia and damping, limiting their ability to suppress external disturbances and fluctuations [1]. Virtual synchronous generator (VSG) technology addresses this issue by emulating the rotational inertia and damping properties of traditional synchronous generators, thereby enhancing microgrid stability through inertial support. However, during grid synchronization, VSGs may still experience high inrush currents and significant voltage harmonics, indicating a need for further research and control improvements.

To enhance the stability of virtual synchronous generators (VSGs) during grid connection, various control strategies have been proposed to improve their dynamic performance. A virtual inertia frequency control method that provides droop characteristics and primary frequency regulation can achieve basic control, but its fixed inertia and damping parameters prolong the frequency recovery process during load changes [2]. An adaptive virtual inertia control scheme based on power angle characteristics reduces power and frequency overshoot by improving dynamic performance, yet it inadequately considers damping's role in frequency stability [3]. An interleaved inertia-damping control strategy employing time-division regulation enhances angular velocity response and frequency stability, but lacks clear damping selection criteria and suffers from discontinuous parameter adjustment issues [4]. The adaptive model predictive control (MPC) approach effectively suppresses grid-connection inrush currents but incurs high computational complexity [5]. The parameter design scheme simplifying phase angle calculation via virtual resistors reduces implementation difficulty but fails to address frequency overshoot risks caused by fluctuations [6].

Existing VSG control methods often suffer from structural complexity, uncoordinated inertia-damping adjustment, and limited dynamic performance. In response, this paper introduces a pre-synchronization strategy based on coordinated adaptive control of virtual inertia and damping. The approach continuously adjusts both parameters in real time using the rate of change and deviation of the rotor angular velocity, eliminating the need for segmented computation and significantly improving transient response. This coordinated control suppresses excessive frequency fluctuations and deviations, enhancing stability during grid synchronization. Simulation results from PSCAD validate that the proposed strategy effectively reduces voltage harmonics and inrush currents, providing a reliable solution for the stable grid integration of renewable energy systems.

## 2 VSG CONTROL PRINCIPLE

The control system emulates synchronous generator behavior through virtual inertia and damping. The PQ outer loop generates reference electromotive force and phase angle, which are processed by a dual voltage-current closed-loop control to produce the reference voltage. SPWM modulation then drives the inverter accordingly.

Based on the second-order model of the traditional synchronous generator motion equations and the relationship between power and torque, the VSG rotor motion equation can be derived as [7]:

$$\begin{cases} T_m - T_e = \frac{P_m}{\omega} - \frac{P_e}{\omega} = J \frac{d\omega}{dt} + D(\omega - \omega_n) \\ \frac{d\theta}{dt} = \omega \end{cases} \quad (1)$$

where,  $\omega$  and  $\omega_n$  are the output and rated angular frequencies,  $\theta$  is the excitation electromotive force phase angle,  $P_m$  and  $P_e$  are the mechanical input power and electromagnetic output power,  $T_m$  and  $T_e$  are the mechanical input torque and electromagnetic output torque, respectively. The electromagnetic torque and power satisfy:

$$T_e = \frac{P_e}{\omega} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (2)$$

The active power output of a synchronous generator is controlled by adjusting its prime mover torque. The governor responds to grid frequency deviations to maintain system stability [7]. Similarly, in a VSG, the active power command is regulated by adjusting the reference mechanical torque  $T_{set}$  and frequency deviation feedback  $\Delta T$ . Thus, the total mechanical torque input  $T_m$  to the VSG comprises  $T_{ref}$  and  $\Delta T$ :

$$T_m = \frac{P_{set}}{\omega} + K_\omega (\omega_0 - \omega) \quad (3)$$

where,  $P_{set}$  represents the given active power;  $K_\omega$  represents the angular frequency deviation adjustment coefficient.

VSG's active power frequency regulation draws upon the prime mover mechanism of synchronous generators, employing  $P$ - $f$  droop control [8]; reactive power voltage regulation simulates excitation regulation functionality, generating voltage magnitude deviation through reactive power deviation and voltage regulation coefficient to achieve  $Q$ - $E$  droop control. Its  $P$ - $f$  and  $Q$ - $E$  droop models are respectively:

$$P_m = P_{set} + \Delta f = P_{set} + D_p (f_{ref} - f) \quad (4)$$

$$E_m = E_{set} + \Delta Q = E_{set} + D_q (Q_{set} - Q) \quad (5)$$

where,  $D_p$  represents the frequency modulation coefficient;  $f_{ref}$  represents the frequency reference value;  $\Delta f$  represents the frequency variation difference;  $E_m$  and  $E_{set}$  represent the reference value and setpoint value of the terminal voltage, respectively;  $Q$  and  $Q_{set}$  represent the actual value and setpoint value of reactive power, respectively;  $\Delta Q$  denotes the reactive power deviation value at the terminal output;  $D_q$  denotes the voltage regulation coefficient.

### 3 IMPROVED ADAPTIVE INERTIA DAMPING PRESYNCHRONIZATION CONTROL

#### 3.1 Influence of Rotational Inertia and Damping on Active and Frequency Responses

Based on the small-signal model of conventional synchronous generators and assuming the VSG output resistance  $R=0$  from (1), the transfer function between active power input and output is approximated as:

$$G(s) = \frac{P(s)}{P_{set}(s)} = \frac{\frac{1}{J\omega_0} \frac{EU}{Z}}{s^2 + \left(\frac{D}{J} + \frac{K_\omega}{J\omega_0}\right)s + \frac{1}{J\omega_0} \frac{EU}{Z}} \quad (6)$$

Based on the typical second-order transfer function (6), the natural oscillation angular frequency  $\omega_n$  and damping ratio  $\xi$  of the corresponding second-order model can be obtained, expressed as:

$$\begin{cases} \omega_n = \sqrt{\frac{EU}{J\omega_0 Z}} \\ \xi = D \sqrt{\frac{EU}{4JEU}} + K_\omega \sqrt{\frac{Z}{4J\omega_0 EU}} \end{cases} \quad (7)$$

From the above equation, we can derive that: when  $0 < \xi < 1$  and the error band is  $\pm 5\%$ , the overshoot and settling time corresponding to the second-order system are respectively

$$\begin{cases} \sigma\% = e^{-\pi\xi/\sqrt{1-\xi^2}} \times 100\% \\ t_s = \frac{3.5}{\xi\omega_n} \end{cases} \quad (8)$$

The dynamic response of the second-order system depends mainly on the rotational inertia  $J$ , damping coefficient  $D$ , and overshoot coefficient  $K_\omega$ . With fixed error gain, increasing  $J$  at constant  $D$  reduces the damping ratio  $\xi$ , resulting in higher overshoot  $\sigma\%$  and longer settling time  $t_s$ . Conversely, increasing  $D$  at fixed  $J$  raises the damping ratio  $\xi$ , reducing overshoot and shortening settling time  $t_s$ .

Thus,  $J$  primarily influences the oscillation frequency in the active power response, while  $D$  governs the decay process. To avoid power oscillations during step changes and ensure stable operation,  $J$  should not be set excessively high.

According to (1), it can be deduced that

$$\begin{cases} \Delta\omega = \frac{T_m - T_e - Jd\omega/dt}{D} \\ \frac{T_m - T_e - T_D}{J} = \frac{d\omega}{dt} \end{cases} \quad (9)$$

where, assuming  $T_m - T_e - Jd\omega/dt$  remains constant, an increase in the damping coefficient  $D$  will reduce the frequency deviation  $\Delta\omega$ . Correspondingly, assuming  $T_m - T_e - T_D$  remains constant, increasing the rotational inertia  $J$  will decrease the angular velocity change rate  $d\omega/dt$ . Therefore, appropriate configuration of  $J$  and  $D$  is essential to suppress the rate of angular velocity change and frequency deviation, thereby maintaining system frequency stability.

### 3.2 Improved Adaptive Inertia Damping Pre-Synchronization Strategy

VSG effectively suppresses system disturbances, but traditional fixed-parameter designs limit dynamic adjustment capabilities [9]. Real-time adjustment of  $J$  and  $D$  during transients could reduce overshoot and enhance dynamic performance. Existing adaptive inertia methods often partition the system into multiple intervals for optimization, leading to computational complexity and limited adaptability due to fixed coefficients, which results in suboptimal performance. This paper proposes a coordinated adaptive control method for inertia and damping. Analysis of the VSG power-angle frequency oscillation curve Figure 1 identifies dynamic adjustment requirements for  $J$  and  $D$  across operational phases, forming the coordinated control criteria in Table 1.

As shown in Figure 1(a), when the VSG's active power increases from  $P_1$  to  $P_2$ , the stable operating point shifts from A to B. Both power and frequency exhibit decaying oscillations with similar dynamic responses. For analysis under fixed  $J$  and  $D$ , the oscillation process is divided into four intervals: ① $t_1-t_2$ , ② $t_2-t_3$ , ③ $t_3-t_4$ , and ④ $t_4-t_5$ , as depicted in Figure 1(b).

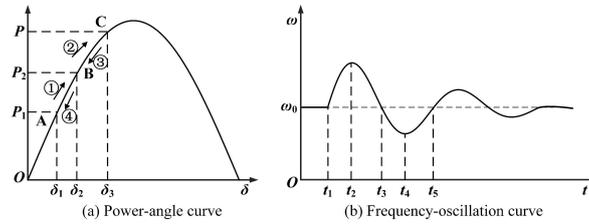


Figure 1 VSG Power-Angle and Frequency-Oscillation Curve

During interval ①, the VSG rotor angular velocity exceeds the grid frequency and continues rising, while angular acceleration  $d\omega/dt$  decreases after an initial abrupt change—to suppress excessive speed rise and limit deviations in  $d\omega/dt$  and  $\Delta\omega$ , both  $J$  and  $D$  should be increased. In interval ②,  $d\omega/dt$  turns negative as deceleration begins; though angular velocity decreases from its peak, it remains above grid frequency, requiring a smaller  $J$  to accelerate return to rated speed and a higher  $D$  to suppress deviation when  $|\Delta\omega|$  is large. Intervals ③ and ④ follow analogous adjustment principles. In summary, the selection of the moment of inertia  $J$  must be based on both the angular velocity change  $\Delta\omega$  and its rate of change  $d\omega/dt$ , while the damping coefficient  $D$  depends solely on  $\Delta\omega$ . The specific selection principles for  $J$  and  $D$  under different operating conditions are shown in Table 1.

Table 1 Principles for Selecting  $J$  and  $D$  Parameters

Time	$\Delta\omega$	$d\omega/dt$	$\Delta\omega(d\omega/dt)$	$J$ -value	$D$ -value
①	>0	>0	>0	Increase	Increase
②	>0	<0	<0	Reduce	Reduce
③	<0	<0	>0	Increase	Increase
④	<0	>0	<0	Reduce	Reduce

Based on the selection principles for inertia and damping in Table 1, and incorporating the mathematical relationship between inertia damping and angular velocity change rate, this paper introduces the arctangent function to propose an adaptive inertia-damping cooperative control strategy, expressed as:

$$\begin{cases} J = J_0 + \frac{K_j \pi}{3} \arctan(\Delta\omega \Delta P), & K_j < J_0 \\ D = \begin{cases} D_0, & |\Delta\omega| \leq T_d \\ D_0 + K_d |\Delta\omega|, & |\Delta\omega| > T_d \end{cases} \end{cases} \quad (10)$$

where,  $J_0$  and  $D_0$  represent the rotational inertia and damping coefficient during stable operation of the VSG, respectively;  $K_j$  and  $K_d$  represent the adjustment coefficients for rotational inertia and damping, respectively;  $T_d$  represents the variation threshold of the damping coefficient. This equation demonstrates that the method eliminates the need for segmented

analysis during inertia optimization, thereby simplifying the calculation process.

To achieve seamless transition from standalone operation to grid connection for VSGs, a control strategy incorporating phase, amplitude, and frequency pre-synchronization is required. Frequency pre-synchronization is achieved by matching local load to adjust prime mover power or through secondary frequency regulation. Phase and amplitude pre-synchronization are accomplished through the control strategy. Based on this, this paper proposes an improved adaptive parameter cooperative pre-synchronization strategy, whose system structure is shown in Figure 2.

This control system takes the grid voltage phase and amplitude as references, compares them with the VSG-side values to compute phase and amplitude deviations. These deviations are processed by a PI regulator to generate an angular frequency correction, which is then superimposed on the VSG frequency command to adjust the output frequency via phase regulation. Pre-synchronization is completed and grid connection is enabled once both deviations reduce to zero.

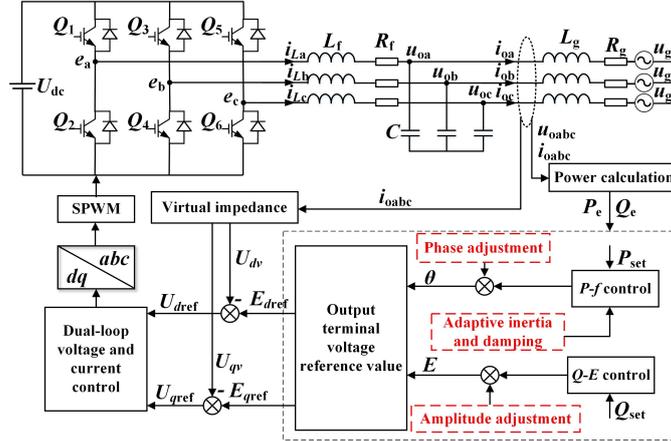


Figure 2 Improved Adaptive Inertia Damping Pre-Synchronization Control Overall Block Diagram

#### 4 SIMULATION ANALYSIS AND VERIFICATION

To validate the theoretical analysis and the proposed improved adaptive parameter pre-synchronization control strategy in this paper, a VSG model was constructed in PSCAD for simulation analysis. Primary simulation parameters:  $U_{dc}=700V$ ;  $L_f=3 \times 10^{-3}mH$ ;  $R_f=0.1\Omega$ ;  $C=20\mu F$ ;  $L_g=4.6 \times 10^{-3}mH$ ;  $R_g=3\Omega$ ;  $J_0=2kg \cdot m^2$ ;  $D_0=20$ ;  $K_\omega=20$ ;  $K_j=0.2$ ;  $K_d=10$ ;  $T_j=2$ ;  $T_d=0.1$ .

##### 4.1 Control Strategy Analysis

Figure 3 (a) and (b) show the dynamic active power response of the VSG under different virtual inertia  $J$  and damping coefficient  $D$ , comparing various droop strategies. Reducing  $J$  at fixed  $D$  decreases inertia, improving initial response but accelerating angular velocity decay. Increasing  $J$  yields smoother deceleration. Raising  $D$  at fixed  $J$  suppresses power fluctuations and oscillations, improving stability at the cost of slower response. Excessively large  $J$  may induce overshoot and oscillations, necessitating careful parameter optimization to balance stability, response speed, and accuracy. Simulations confirm that  $J$  governs oscillation frequency, while  $D$  reduces overshoot and shortens settling time, providing a theoretical basis for VSG control optimization.

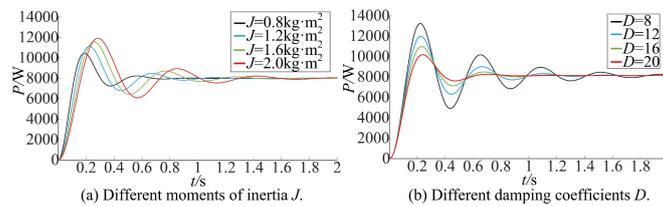
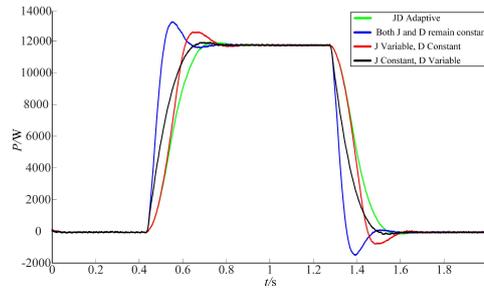
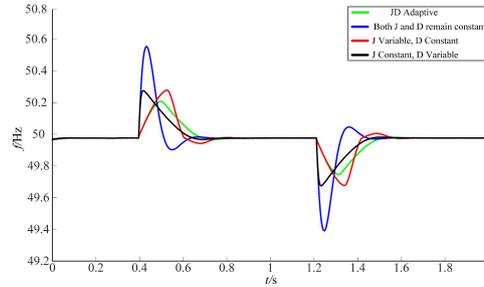


Figure 3 Active Power Response under Different Control Parameters

Figure 4 and Figure 5 compare the step responses of active power and output frequency under different VSG control strategies. The fixed-parameter control exhibits the largest overshoot, longest settling time, and significant frequency deviation during power transients. Adjusting the virtual inertia reduces both active power overshoot and frequency deviation, while increasing the damping coefficient shortens settling time and accelerates frequency stabilization. The adaptive JD strategy simultaneously improves all metrics, achieving minimal overshoot, deviation, and the fastest stabilization.



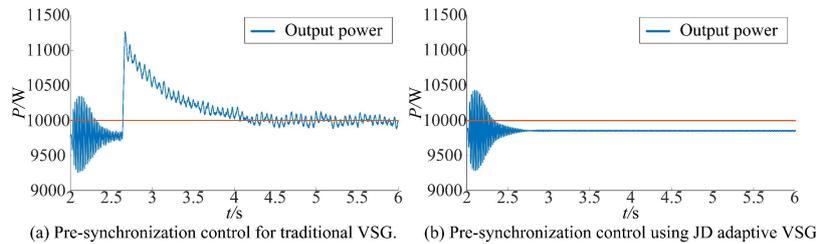
**Figure 4** Active Power Response under Different Control Strategies



**Figure 5** Frequency Response under Different Control Strategies

**4.2 Pre-synchronization Verification**

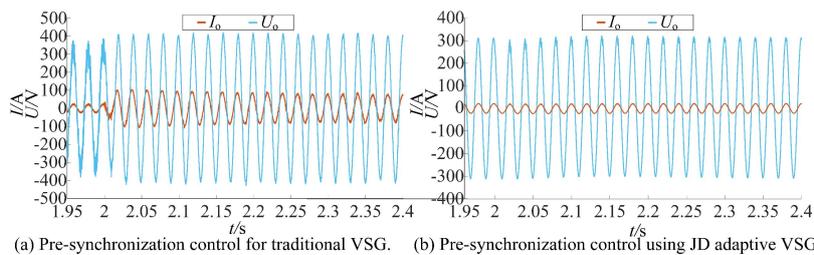
A test scenario with maximum phase deviation and 10 kW active power is used to evaluate the proposed pre-synchronization strategy. The VSG operates in standalone mode before grid connection at  $t = 2$  s. Simulation results demonstrate the control effectiveness and stability.



**Figure 6** Pre-Synchronization Active Power Comparison

Figure 6 (a) shows conventional VSG pre-synchronization without adaptive JD control. Grid connection is achieved around 2.6 s, but active power exhibits surges and fluctuations caused by voltage harmonics and inrush currents. In contrast, Figure 6 (b) demonstrates that adaptive JD control maintains stable active power after synchronization by suppressing frequency deviations and transients, ensuring system stability without power disturbances.

Figure 7 (a) shows that under traditional VSG control, the converter output voltage displays significant harmonic distortion and overvoltage before grid connection, along with current surges. Both voltage and current fluctuate considerably during the transition. In contrast, Figure 7 (b) demonstrates that the JD adaptive VSG control maintains stable voltage and current throughout the process, effectively suppressing harmonics and inrush currents during synchronization.



**Figure 7** Pre-Synchronization Output Voltage and Current Comparison

**5 CONCLUSION**

A coordinated adaptive pre-synchronization control strategy for VSGs is proposed, which adjusts both inertia and

damping to suppress inrush currents and voltage harmonics during grid connection. By establishing the relationships between rotational inertia and frequency change rate, and between damping coefficient and frequency deviation, the method adaptively coordinates  $J$  and  $D$  to suppress excessive frequency variations. The strategy improves dynamic response and stability while mitigating voltage harmonics. A zero-deviation regulation method is also introduced to eliminate standalone operational deviations, resulting in smoother waveforms and enhanced power quality throughout the synchronization process.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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