Research Article

Suppression Strategy of Subsynchronous Oscillation Based on Dynamic Voltage Compensation Control for Grid-Forming D-PMSG in Weak Grid

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The virtual impedance can suppress the low-frequency oscillation effectively caused by the power coupling effect for the grid-forming direct-drive permanent magnet synchronous generator (D-PMSG). However, there are few studies on the influence of virtual impedance on the subsynchronous oscillation caused by the interaction between the grid-forming D-PMSG and the weak grid. In this paper, the mechanism of virtual impedance improving the stability of virtual synchronous generator (VSG) control for the converter is revealed from the perspective of power coupling, and the influence of virtual impedance on the system stability in subsynchronous frequency range was analysed based on the sequence impedance model. The analysis results show that the virtual inductance cannot effectively improve the oscillation suppression effect, but the virtual resistance can greatly improve the damping characteristics of the system which has a good oscillation suppression effect. However, excessive increase in virtual resistance will cause power coupling oscillation, even subsynchronous oscillation, which shows limitations in subsynchronous oscillation suppression. To solve the problem, a dynamic voltage compensation control method based on active disturbance rejection control (ADRC) was proposed, and the parameters are designed by bandwidth method. The method can suppress the subsynchronous oscillation effectively in a certain frequency range under different grid strength and disturbance conditions. And it shows strong adaptability and good system robustness in weak grid. Finally, the effectiveness of the proposed oscillation suppression strategy was verified by time domain simulation.

1. Introduction

Under the background of continuous growth of global wind power installed capacity, to make up for the lack of system inertia caused by the introduction of high proportion power electronic equipment, the grid-forming VSG control technology is applied to the grid-side converter of D-PMSG, which provides inertia support to the power system by mimicking the transient characteristics of synchronous generator [1–3]. Under the condition of high proportion power electronic equipment, the interaction between D-PMSG and the weak grid is prone to subsynchronous oscillation, which is particularly prominent in remote areas [4, 5]. The virtual impedance can suppress the low-frequency oscillation effectively caused by the power coupling effect for the grid-forming D-PMSG. However, there are few studies on the influence of virtual impedance on the subsynchronous oscillation caused by the interaction between the grid-forming D-PMSG and the weak grid [6, 7]. The paper will focus on this issue to carry out research.

The sequence impedance analysis method is widely used in the stability analysis of new energy grid connection because of its easy engineering measurement and simple form [8–10]. The mechanism and characteristics of the subsynchronous oscillation in weak grid were analysed according to distribution characteristics of the impedance model for D-PMSG in the frequency domain [11, 12]. The equivalent capacitive characteristics of D-PMSG interact with the inductive characteristics of the weak grid and generate electrical resonance. Then, the subsynchronous oscillation occurs with resonance divergence under the equivalent...
negative damping impact of phase-locked loop [13]. To avoid the negative damping impact and provide inertia support to the power system, the grid-forming VSG control was proposed to apply in the grid-side converter of D-PMSG [14, 15].

The rotor motion state equation is introduced in VSG control which is based on the droop control to mimic the characteristics of the synchronous generator (SG) [16]. Compared with traditional vector control, VSG control could provide inertia support to the system and avoid the negative damping effect caused by the phase-locked loop [17]. Hence, VSG control is widely used in new energy grid-connected operation under the background of the high proportion of power electronic equipment. However, due to the influence of its own control structure, the problem of power coupling oscillation will be generated inevitably [18]. To solve the problem of low-frequency oscillation caused by power coupling, supplementary damping controllers have been introduced into the power loop [19]. This method can improve the damping characteristics and the stability of the system, but it cannot change the power coupling effect of VSG. Considering the power decoupling, the virtual impedance was introduced to eliminate the coupling effect, which can suppress the low-frequency oscillation effectively [20]. In References [21, 22], the virtual impedance was used to improve the transient stability in the microgrid. Reference [23] uses virtual impedance to change the output impedance of the HVDC system and improve the transmission capacity of the system. In addition, the virtual impedance could be used to improve the quality of output current [24]. The virtual impedance can suppress the reactive circulation by keeping the symmetry of the line impedance in the multi-VSG system and improve the stability of the system [25]. In Reference [26], the virtual impedance is combined with inertia to improve the response speed of system frequency. To achieve accurate voltage control, voltage-current double closed loop was often introduced into VSG. But the subsynchronous oscillation will occur easily when interacting with the weak grid. It can be known from Table 1 that the virtual impedance could suppress the power coupling oscillation effectively within several hertz. However, there are limitations in the suppression of subsynchronous oscillation from several hertz to 50 Hz. To solve the problem, a dynamic voltage compensation control method based on ADRC was proposed. This method could suppress the subsynchronous oscillation in a certain frequency range and show strong robustness. Finally, the effectiveness of the proposed oscillation suppression strategy was verified by time domain simulation.

Compared to the previous research, the main contributions of this article are as follows: First, the mechanism of virtual impedance improving the stability of grid-forming converter is revealed from the perspective of power coupling. Second, the analysis results based on the sequence impedance model provide a theoretical basis for the study of virtual impedance to improve the stability in the subsynchronous range. Third, the ADRC controller parameters were designed by the bandwidth method, which could suppress the subsynchronous oscillation in a certain frequency range and show strong robustness. And it could provide a reference for the study of oscillation suppression methods.

This paper is constructed as follows: The topology and control scheme of grid-forming D-PMSG is introduced in Section 2. In Section 3, the influence of virtual impedance on system stability is analysed. And the dynamic voltage compensation control based on ADRC is designed in Section 4. In Section 5, the effectiveness of the proposed oscillation mitigation strategy is verified by simulation experiments. Finally, Section 6 concludes this article.

2. Topology and Control Scheme of Grid-Forming D-PMSG

2.1. Mathematical Model of PMSG. The stator voltage equation in three-phase stationary reference frames can be expressed as formula (1) by the Kirchhoff circuit theory and electromagnetic induction law.

\[ \begin{align*}
\psi_{sa}(t) &= -R_s i_{sa}(t) + \frac{d\psi_{sa}(t)}{dt}, \\
\psi_{sb}(t) &= -R_s i_{sb}(t) + \frac{d\psi_{sb}(t)}{dt}, \\
\psi_{sc}(t) &= -R_s i_{sc}(t) + \frac{d\psi_{sc}(t)}{dt},
\end{align*} \]

where \( R_s \) is stator winding resistance; \( \psi_{sa}(t), \psi_{sb}(t), \) and \( \psi_{sc}(t) \) are stator terminal voltage, respectively; \( i_{sa}(t), i_{sb}(t), \) and \( i_{sc}(t) \) are stator current, respectively; and \( \psi_{sa}(t), \psi_{sb}(t), \) and \( \psi_{sc}(t) \) are three-phase winding flux linkages, respectively.

Stator flux equation can be written as follows:

\[ \begin{align*}
\psi_{sa} &= (L_{sa} + L_m) i_{sa} + \psi_f \cos \theta_t, \\
\psi_{sb} &= (L_{sa} + L_m) i_{sb} + \psi_f \cos (\theta_t - 120^\circ), \\
\psi_{sc} &= (L_{sa} + L_m) i_{sc} + \psi_f \cos (\theta_t + 120^\circ),
\end{align*} \]

where \( \psi_f \) is rotor flux linkage, \( L_m \) is equivalent excitation inductance, and \( L_{sa} \) is leakage inductance.

The electromagnetic torque equation can be obtained as follows:

\[ T_e = n_p \psi_s \times i_s, \]

where \( n_p \) is the number of pole pairs, \( \psi_s \) is stator flux vector, and \( i_s \) is stator current vector.

2.2. The Basic Principle of VSG Control. The rotor-side converter of grid-forming D-PMSG adopts voltage-current double closed loop control strategy. The grid-side converter adopts grid-forming VSG control strategy, which includes power outer loop and voltage-current inner loop control. Its main topology and control structure are shown in Figure 1.

The rotor motion state equation is introduced in VSG control which is based on the droop control in active power loop to mimic the transient characteristics of the SG. It could participate in system frequency regulation and provide inertial support to improve the frequency stability of the power system. The excitation voltage equation is also applied in the reactive power loop to regulate the bridge arm potential of the grid-side converter, and the terminal voltage can be accurately controlled by voltage and current double closed loop.
3. Sequence Impedance Modeling and Stability Analysis of Grid-Side Converter-Based VSG

3.1. Mechanism Analysis of Virtual Impedance to Improve the Stability of Grid-Side Converter. The output power transmission diagram of the distributed power is shown in Figure 2. The voltage $U_g$ is the public bus voltage. $E_0$ is the output voltage of distributed power. $Z$ and $Z_C$ are the equivalent impedance of the output line and virtual impedance. $\delta$ and $\theta$ are power angle differences and impedance angle.

According to Figure 2, the mathematical model of power transmission can be written as

$$
S = 3U_g^* = P_e + jQ_e,
$$

$$
P_e = \frac{3U_g}{\sqrt{R^2 + X^2}} \left( E_0 \cos \left( \arctan \frac{R}{X} - \delta \right) - U_g \cos \theta \right),
$$

$$
Q_e = \frac{3U_g}{\sqrt{R^2 + X^2}} \left( E_0 \sin \left( \arctan \frac{R}{X} - \delta \right) - U_g \sin \theta \right).
$$

(4)

It can be seen from formula (4) that there is a strong coupling relationship between active power and reactive power due to the impedance angle. This coupling characteristic will affect the stability of the system and even generate power coupling oscillation. To realize the decoupling of active and reactive power, it is necessary to keep the line mainly inductive. It means that the impedance angle $\theta$ needs to be set to $\pi/2$.

The power angle $\delta$ is usually quite small; then, $\sin \delta \approx \delta$. Therefore, formula (4) can be simplified to

$$
P_e = \frac{3U_g}{\sqrt{R^2 + X^2}} E_0 \delta,
$$

$$
Q_e = \frac{3U_g}{\sqrt{R^2 + X^2}} (E_0 - U_g).
$$

(5)

From formula (5), it can be seen that the active power is related to the power angle, and the reactive power is related to the voltage, and both of them are decoupled. The traditional droop control and VSG control are based on formula 2: Summarization of literature review.

<table>
<thead>
<tr>
<th>Reference</th>
<th>VSG</th>
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Figure 1: Main topology and control structure of grid-forming D-PMSG.
where the expression of VSG output phase angle is expressed as

\[ \frac{1}{s (s + D)} \left( \frac{P_{\text{ref}}}{\omega_0} + D \omega_0 - \frac{P}{\omega_0} \right). \]  

(9)

Substituting (7) into (9) and neglecting quadratic term of small signal, the frequency domain expression of VSG output phase angle can be obtained as

\[
\theta[f] = \left\{ \begin{array}{l}
M(s) \left[ \frac{P_{\text{ref}}}{\omega_0} + D \omega_0 - \frac{3}{\omega_0} (V_1 I_1^* + V_2 I_2^*) \right], \text{dc}, \\
-3M(s) \left( \frac{V_1 I_1^* + V_2 I_2^* + V_1 I_2 + V_2 I_1}{\omega_0} \right), f = \pm (f_p - f_0),
\end{array} \right.
\]

(10)

where \( M(s) = 1/[s^* (s + D)] \), \( \theta = \theta_0 + \Delta \theta \), and \( \theta_0 = \omega_0 t + \varphi_{\text{vir}} \); \( \omega_0 f \) is the voltage fundamental phase, and \( \varphi_{\text{vir}} \) is the initial phase.

Similarly, according to excitation voltage equation, the frequency domain expression of bridge arm potential amplitude \( E \) can be obtained as follows:

\[
E[f] = \left\{ \begin{array}{l}
N(s) \left[ Q_{\text{ref}} - 3 (-jV_1 I_1^* + jV_1 I_1^*) + K_q (U_n - U_0) \right], \text{dc}, \\
\pm N(s) 3 j (V_1 I_1^* + V_2 I_2^* - V_1 I_2 + V_2 I_1), f = \pm (f_p - f_0),
\end{array} \right.
\]

(11)

where \( N(s) = 1/K_s \).

3.2.2. The Model of Voltage-Current Double Closed Loop. Frequency domain expression of voltage out loop reference value is given as

\[
\begin{bmatrix} V_{\text{dref}}[f] \n V_{\text{qref}}[f] \end{bmatrix} = \begin{bmatrix} E[f] \n -V_{\text{vd}}[f] \end{bmatrix},
\]

(12)

where \( V_{\text{vd}} \) and \( V_{\text{vq}} \) are voltage drop of virtual impedance, and it can be expressed in frequency domain as follows:

\[
\begin{bmatrix} V_{\text{vd}}[f] \n V_{\text{vq}}[f] \end{bmatrix} = \begin{bmatrix} R_v I_{1d} - \omega_0 L_v I_{1q} \n R_v I_{1d} + \omega_0 L_v I_{1q} \end{bmatrix}.
\]

(13)

According to (14), converting the three-phase output voltage signal to two phase dq axis reference frame. The \( \theta \) adopts VSG output phase angle. Frequency domain expressions of the trigonometric function and the Park transformation matrix are shown in (A.5)–(A.11).

\[
\begin{bmatrix} v_d \\ v_q \end{bmatrix} = T(\theta) \begin{bmatrix} v_a \\ v_b \end{bmatrix}.
\]

(14)

Applying the Laplace transform to (14), the frequency domain expression of output voltage in dq axis reference frames can be obtained as
The sequence impedance expression in dq axis reference frames can be expressed as

\[ V_d[f] = \frac{3V_1 \sin \varphi_{vir}}{s(Js + D)\omega_0} (V^*_1p_1 + V_p I^*_1 + V_1p_2 + V_2p_1) + V_p e^{j\varphi_{vir}} + V_2p e^{j\varphi_{vir}}, f = \pm (f_p - f_0), \]

\[ V_q[f] = \frac{-V_1 \sin \varphi_{vir}}{s(Js + D)\omega_0} (V^*_1p_1 + V_p I^*_1 + V_1p_2 + V_2p_1) + jV_p e^{j\varphi_{vir}} \pm jV_2p e^{j\varphi_{vir}}, f = \pm (f_p - f_0). \]

where \( e_s \) is the bridge arm potential, \( V_{dc} \) is the DC side voltage, \( K_m \) is the modulation coefficient, and \( C_a \) is the modulation signal of phase A after the inverse Park transform for (17).

The current frequency response equivalent circuit is shown in Figure 3, and the current frequency response expression can be expressed as follows:

\[ I_s[f] = \frac{\hat{\bar{e}}_s[f_p]}{sL_I + R_I} \left[ \frac{C_I L_I^2 s + sC_I (R_c + R_f) + 1}{sC_I R_c + 1} \right] \hat{f}_p \]

(20)

The sequence impedance in frequency domain can be expressed as

\[ Z[f] = -\frac{\hat{f}_p}{\hat{I}_s[f_p]} \]

(21)

Neglecting coupling effect, the positive and negative sequence impedance expressions can be obtained as

\[ Z[f] = \frac{(3/4) V_1 G_{1c} G_c \bar{N}(s)e^{j(\varphi_m - \pi/2)} + (3V_1/4a_0)M(s)H(s)e^{j\varphi_{vir}} - G_c G_{1d} + (G_{1d} + G_{1d})(1 + (R_c + L_c)(s + j\omega_a))K_m V_{dc})}{(3/4) G_{1c} G_c \bar{N}(s)e^{j(\varphi_m - \pi/2)} + (3I_f/4a_0)M(s)H(s)e^{j\varphi_{vir}} - G_c G_{1d} + (G_{1d} + G_{1d})(1 + (R_c + L_c)(s + j\omega_a))K_m V_{dc}), s = j2\pi(f_p - f_0). \]

(22)

where

\[
\begin{align*}
G_{1d} &= G_c G_s m G_c a_0 C_f - 1, \\
G_{1d} &= \pm G_c G_s a_0 C_f m, \\
G_a &= k_m + \frac{k_m}{s}, G_b &= k_p + \frac{k_p}{s}, \\
G_{1d} &= G_m a_0 L_f \pm G_c G_s a_0 d + G_c G_c R_f, \\
G_{1d} &= \pm G_f + a_0 L_f \pm G_c G_c R_f, \\
H(s) &= G_m V_1 \sin \varphi_{vir} + G_m V_1 \cos \varphi_{vir} - G_c I_1 \sin (\varphi_{vir} - \varphi_c) m j G_I I_1 \cos (\varphi_{vir} - \varphi_c) + G_{1d} I_1 \sin (\varphi_{vir} - \varphi_c) + G_{1d} I_1 \sin (\varphi_{vir} - \varphi_c) - (\hat{e}_s m j \hat{c}_o). 
\end{align*}
\]

(23)
3.3. Stability Analysis for VSG in Weak Grid. The stability characteristics of grid-side converter-based VSG are shown in Figure 4. It can be seen from the phase-frequency curve that the negative sequence impedance of the grid-side converter presents inductive within 100 Hz, while the positive sequence impedance presents capacitive characteristics as a whole. Especially in the range of 20 Hz-44 Hz, the positive sequence impedance phase is lower than -90° which shows the characteristics of negative damping and capacitance. It can be seen from the amplitude-frequency curve that there is an intersection. It is between the positive sequence impedance curve and the weak grid impedance curve at 30 Hz, and the system loses stability when the phase difference exceeds 180°. The equivalent capacitance of the grid-side converter interacts with the inductive characteristics of weak grid and generates electrical resonance, which is easy to diverge and produce subsynchronous oscillation under the impact of negative damping. Therefore, the grid-forming D-PMSG has the risk of instability under weak grid conditions.

3.4. Influence of Virtual Impedance on Grid-Side Converter Stability. It can be known from the literature analysis that the virtual impedance can suppress the low-frequency oscillation effectively caused by power coupling within several hertz, but there are few studies focused on the suppression of subsynchronous oscillation of several hertz to 50 Hz. The sequence impedance model of the grid-side converter was established, and the influence of the virtual impedance on the system stability in the subsynchronous frequency range was analysed.

3.4.1. Influence of \( L_v \) on Grid-Side Converter Stability. The influence of \( L_v \) on grid-side converter stability is shown in Figure 5. The resonance frequency increases with \( L_v \) which increases from the amplitude-frequency curve. Due to the weakening of the system capacitance, the intersection point with the grid impedance shifts slightly to the right, which is beneficial to stay away from the negative damping interval. But the overall change is relatively small. The phase-frequency curve shows that the negative damping interval of the system expands obviously with the increase of \( L_v \) within 100 Hz. The negative damping interval is expanded obviously, and the system stability is weakened. It will further aggravate the risk of subsynchronous oscillation. Above 100 Hz, the positive and negative sequence impedances show transient inductive and negative damping characteristics, and the curves gradually overlap. The system near 1000 Hz is capacitive again due to the impact of the output filter capacitor. Therefore, the subsynchronous oscillation is not suppressed by increasing the virtual inductance.

3.4.2. Influence of \( R_v \) on Grid-Side Converter Stability. The influence of \( R_v \) on the grid-side converter stability is shown in Figure 6. The positive and negative sequence impedance amplitude gains decrease with the increase of the virtual resistance \( R_v \) from the amplitude-frequency curve, but the overall change is relatively small. The phase-frequency curve shows that the positive sequence impedance within 100 Hz is capacitive and decreases with the increase of \( R_v \) while the negative sequence impedance is inductive and decreases with the increase of \( R_v \). Especially, the negative damping interval of positive sequence impedance reduced significantly with the increase of \( R_v \) from the initial 20 Hz-44 Hz frequency range. It reduces the risk of subsynchronous oscillation greatly in grid-forming D-PMSG and improves system stability. The positive and negative sequence impedance curves above 100 Hz gradually coincide and are inductive. The system near 1000 Hz is capacitive again due to the influence of the output filter capacitor. Therefore, increasing the virtual resistance could reduce the risk of subsynchronous oscillation in grid-forming D-PMSG.

3.5. Influence of Virtual Resistance on Power Coupling. Although increasing the virtual resistance is beneficial to suppress the system oscillation for grid-forming D-PMSG in weak grid, it will deepen the coupling degree between active power and reactive power and even further affect the system stability.

According to formula (4), a small disturbance model corresponding to the steady state can be written as

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = \begin{bmatrix}
\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial E} \\
\frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial E}
\end{bmatrix} \begin{bmatrix}
\Delta \delta \\
\Delta E
\end{bmatrix}
\]

(24)

where \( E_c = \delta_0 + \arctan (R/X) \) and \( E_0 \) and \( \delta_0 \) are the bridge arm potential and power angle at stable operating point.

To analyse power coupling degree quantitatively, the relative gain matrix analysis method (RGA) is used [28]. According to Reference [20], the relative gain matrix can be listed as

\[
\text{RGA} = \begin{bmatrix}
\lambda_{11} & \lambda_{12} \\
\lambda_{21} & \lambda_{22}
\end{bmatrix} = \begin{bmatrix}
\cos^2 \gamma_c & \sin^2 \gamma_c \\
\sin^2 \gamma_c & \cos^2 \gamma_c
\end{bmatrix},
\]

(25)

where \( \lambda_{12} \) represent the coupling coefficient \( K_A \).

The relationship between coupling coefficient \( K_A \) and virtual resistance is shown in Figure 7. When the power angle and virtual inductance remain constant, the coupling coefficient between active and reactive power increases as the virtual resistance increases. Therefore, increasing the virtual resistance will deepen the power coupling and even cause power coupling oscillation.
Figure 4: Stability analysis based on sequence impedance.

Figure 5: Influence of virtual inductance on grid-side converter stability.
From above analysis, it can be known that increasing virtual inductance could weaken the system capacitance to a certain extent and shift the resonant frequency to the right, but the shift amplitude is limited. And the negative damping interval expands significantly with the virtual inductance increasing, which further aggravates the risk of subsynchronous oscillation, while increasing the virtual resistance can narrow the negative damping interval significantly and reduce the risk of subsynchronous oscillation. However, increasing the virtual resistance will deepen the coupling degree between active power and reactive power and even increase the risk of power coupling oscillation. There are limitations on the subsynchronous oscillation suppression by increasing the virtual resistance. Hence, a dynamic voltage compensation control method based on ADRC was proposed in this paper.

4. The Design of Dynamic Voltage Compensation Control Based on ADRC

4.1. The Basic Principles of ADRC. Active disturbance rejection control has strong robustness and high control precision, which is an effective way to solve the problem of nonlinear systems [29, 30]. Taking the second-order control system as an example, the ADRC mainly includes three parts: nonlinear differential tracker, extended state observer, and nonlinear state error feedback. The basic control structure of ADRC is shown in Figure 8.
Second-order system can be expressed as follows:

\[
\begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= f(x_1, x_2) + bu, \\
y &= x_1,
\end{align*}
\]

(26)

where \(x_1\) and \(x_2\) are the state variables of the controlled object; \(f(x_1, x_2)\) is an unknown function, which contains the lumped disturbance and the uncertain part of the system; \(u\) is the system control input; \(y\) is the system control output; and \(b\) is the feedback coefficient. Let \(x_3 = f(x_1, x_2)\), \(\dot{x}_3 = f_0\).

The ADRC controller is designed according to the following steps:

1. Arranging the transition process with the set value \(v\) as input

\[
\begin{align*}
e &= v_1 - v, \\
f_{\text{han}} &= \text{fhan}(e, v_2, r_0, h_0), \\
v_1 &= v_1 + hv_2, \\
v_2 &= v_2 + h f_{\text{han}},
\end{align*}
\]

(27)

where \(v\) is the input of the ADRC system, \(v_1\) and \(v_2\) are the output of tracking differentiator, \(r_0\) is the velocity factor, \(h_0\) is the filtering factor, \(h\) is the simulation step length, and \(\text{fhan}\) is the fastest feedback function.

\[
u = \text{fhan}(x_1, x_2, r, h):
\]

\[
\begin{align*}
d &= rh, \\
d_0 &= hd, \\
y &= x_1 + hx_2, \\
a_0 &= \sqrt{d^2 + 8r|y|}, \\
a &= \begin{cases} x2 + \frac{(a_0 - d)}{2} \text{sign} (y), & |y| > d_0, \\
x2 + \frac{y}{h}, & |y| \leq d_0, \end{cases}
\end{align*}
\]

(28)

(30)

\[
\text{fanh} = \begin{cases} r \text{sign} (a), & |a| > d, \\
r \frac{a}{d}, & |a| \leq d. \end{cases}
\]

where \(\beta_{01}, \beta_{02},\) and \(\beta_{03}\) are a set of parameters

2. The extended state observer (ESO) uses output \(y\) and input \(u\) to track the system state variables \(x_1\) and \(x_2\) and sets the estimated value of the state variable to \(z_1\) and \(z_2\). The disturbance variable is extended to a new state variable \(x_3\), which is estimated to be \(z_3\)

\[
\begin{align*}
e &= z_1 - y, f e = \text{fale}(\alpha, \beta_1, \beta_2), f e_1 &= \text{fale}(\alpha, \beta_1, \beta_2), \\
z_1 &= z_1 + h(z_2 - \beta_{01} e), \\
z_2 &= z_2 + h(z_3 - \beta_{02} f e + b_0 u), \\
z_3 &= z_3 + h(-\beta_{03} f e_1),
\end{align*}
\]

(29)

\[
\text{fale}(\alpha, \beta_1, \beta_2) = \begin{cases} \frac{e}{\beta_1 - \alpha}, & |e| \leq \delta, \\
|e|^\alpha \text{sign} (e), & |e| > \delta,
\end{cases}
\]

(31)

(32)

where \(p\) is a set of parameters

3. State error feedback law is presented as follows:

\[
\begin{align*}
e_1 &= v_1 - z_1, e_2 &= v_2 - z_2, \\
u_0 &= k(e_1, e_2, p),
\end{align*}
\]

(4) Disturbance compensation process is presented as follows:

\[
u = \frac{u_0 - z_3(t)}{b_0},
\]

where \(b_0\) is the compensation factor
4.2. The Parameter Design of ADRC. The error equation (33) can be obtained by subtracting (26) from (29).

\[
\begin{align*}
\epsilon_01 &= z_1 - x_1, \\
\epsilon_02 &= z_2 - x_2, \\
f \epsilon &= f_{a1}(\epsilon_01, \alpha_1, \delta), f_{e1} = f_{a1}(\epsilon_01, \alpha_2, \delta), \\
\epsilon_01 &= \epsilon_02 - \beta_{01} \epsilon_01, \\
\dot{\epsilon}_02 &= \epsilon_03 - \beta_{02} f \epsilon, \\
\dot{\epsilon}_03 &= -f_0 - \beta_{03} f \epsilon_1.
\end{align*}
\]

(33)

Take \(\alpha_1 = 0.5, \alpha_2 = 0.25, \delta = 0.05, \) and \(a_1 = a_2 = 0.\) Using bandwidth method [30] and applying the Laplace transform to equation (33), the transfer function between lumped disturbance error \(\epsilon_03\) and disturbance \(f\) can be expressed as

\[
\epsilon_03 = -\frac{s^3 + \beta_{01} s^2 + 4.5 \beta_{02} s + 9.46 \beta_{03}}{s^3 + \beta_{01} s^2 + 4.5 \beta_{02} s + 9.46 \beta_{03}} f,
\]

(34)

where \(\beta_{01} = 3 \omega_c, \) \(4.5 \beta_{02} = 3 \omega_c^2, \) and \(9.46 \beta_{03} = \omega_c^3; \) \(\omega_c\) is the bandwidth of extended state observer.

It can be seen from Figure 9 that the amplitude gain curve shifts to the right with the increase of \(\omega_c\) and the disturbance attenuation interval expands in the lower frequency band. The amplitude gain is required to be negative at 50 Hz, and the lumped disturbance error converges to stable quickly in 0 to 50 Hz. When the bandwidth \(\omega_c\) is larger, the accuracy of the extended state observer is higher, and the influence of noise is also greater. Considering comprehensively, the bandwidth \(\omega_c\) of the extended state observer is set as 400 rad/s; \(b_0\) as the compensation factor is mainly used to regulate the compensation voltage which is set as 14.3.

The dynamic voltage compensation control structure based on ADRC is shown in Figure 10. The inductor current is used as control variable, and the compensation voltage is used as control input. To suppress the subsynchronous oscillation and improve the robustness of the system, the dynamic compensation voltage is generated continuously by observing the harmonic component of the inductor current. The dynamic compensation voltage without changing the virtual resistance parameter was used to offset the harmonic voltage drop in the virtual impedance part and suppress the subsynchronous oscillation well in weak grid. This method solves the problem of power coupling oscillation caused by increasing the virtual resistance.

5. Simulation Experiment Results

To verify the effectiveness of the proposed control strategy, a model of 3 MW grid-forming D-PMSG is established on MATLAB/Simulink software platform. The simulation parameters are shown in Table 2.
5.1. Simulation Results under Different Grid Strength Conditions. The grid impedance was switched from normal value to 0.17 mH at 0.8 s; then, short circuit ratio (SCR) < 3 was used to simulate the weak grid. The oscillation of output current occurred at 30 Hz, while the oscillation of active and reactive power occurred at 20 Hz, as shown in Figure 11. The dynamic voltage compensation control was started at 1.8 s, and the grid inductance was switched back to normal at 3 s.

It can be seen from Figure 12(a) that after the dynamic voltage compensation control was started at 1.8 s, the active power and reactive power of the system were attenuated to stable quickly from the maximum oscillation amplitude of 0.33 MW and 0.38 Mvar. And the output current was also stabilized through several cycles of adjustment. The grid inductance was switched to 0.22 mH to simulate a weaker grid at 0.8 s. As shown in Figure 12(b), the oscillation amplitude of the system became larger than before. But after the dynamic voltage compensation control started at 1.8 s, the system oscillation gradually disappeared. Although the oscillation amplitude and frequency changed with the weakening of grid strength, the system still converged to stable through a short adjustment. Therefore, the dynamic voltage compensation control based on ADRC can suppress the subsynchronous oscillation in a certain grid strength range, which shows strong adaptability in weak grid.

5.2. Simulation Results of Terminal Voltage Step Disturbance. The subsynchronous oscillation in grid-forming D-PMSG occurred when the grid inductance was switched from normal to 0.22 mH at 0.8 s. The dynamic voltage compensation control was started, and 3.5% rated voltage step disturbance was applied at 1.8 s. The disturbance was removed at 2.7 s; then, the grid inductance was switched back to normal at 3 s. It can be seen from Figure 13 that the system output power and current oscillation were still suppressed effectively under voltage disturbance conditions. The reactive power drops down 0.77 Mvar which is affected by the droop coefficient and still converged to stable rapidly and shows strong anti-interference ability.
5.3. Simulation Results of Active Power Command Step Disturbance. The grid inductance was switched from normal to 0.22 mH at 0.8 s, and then, the subsynchronous oscillation of the system occurred. The dynamic voltage compensation control was started at 1.8 s, and 1 MW active power command step disturbance was applied. The disturbance was removed at 2.7 s, and then, the grid inductance was switched back to normal at 3 s. It can be seen from Figure 14 that the output power and current oscillation of the system converged to stable by short adjustment, which is only a few cycles of adjustment time more than that without disturbance and shows good system robustness.

5.4. Simulation Results of Increasing Virtual Resistance. The grid inductance was switched to 0.22 mH at 0.8 s, and then, the subsynchronous oscillation of the system occurred. The dynamic voltage compensation control was started, and 0.024 Ω virtual resistance was applied at 1.8 s. The virtual resistance continuously increased to 0.05 Ω at 2.5 s. The
resistance was decreased to 0.024 Ω, and the grid inductance was switched back to normal at 3.0 s. It can be seen from Figure 15 that the system oscillation has a faster convergence speed and better stability than the case without virtual resistance during 1.8 to 2.5 s. The power curve diverged to form a new oscillation with the virtual resistance increasing to 0.05 Ω after 2.5 s. Therefore, increasing the virtual resistance within a certain range is beneficial to improve the stability of grid-forming D-PMSG. However, increasing the virtual resistance continuously will deepen the power coupling effect and form a new power coupling oscillation, which is not conducive to the stability of the system. The oscillation suppression method on ADRC and virtual resistance is compared in Table 3.

The above simulation results are consistent with the theoretical analysis. There are limitations in solving the oscillation suppression problem by simply increasing the virtual resistance. The dynamic voltage compensation control based on ADRC can effectively mitigate the subsynchronous oscillation for grid-forming D-PMSG in weak grid and avoid the problems of power coupling oscillation caused by increasing virtual resistance.

From the simulation analysis, it can be seen that the virtual resistance can improve the oscillation suppression effect, but the continuous increase will deepen the power coupling and form a new power coupling oscillation. Meanwhile, this method needs to change the virtual resistance parameter frequently, which shows weak adaptive ability and poor robustness. The dynamic voltage compensation control can suppress the subsynchronous oscillation in a certain grid strength range without changing the virtual resistance parameter. However, the harmonic current oscillation amplitude increases, and the dynamic compensation control accuracy decreases in the face of a weaker grid. Combining the virtual resistance and dynamic voltage compensation control can not only further improve the oscillation suppression effect but also maintain sufficient control accuracy in the face of a weaker grid and reduce the pressure of ADRC parameter design greatly. Therefore, how to determine the virtual resistance boundary range of power coupling oscillation and combine ADRC with virtual resistance to improve the effect of subsynchronous oscillation suppression is the direction of further research.

### 6. Conclusion

In this paper, the influence of the virtual impedance on the subsynchronous oscillation caused by the interaction between the grid-forming D-PMSG and the weak grid was analysed, and a dynamic voltage compensation method based on ADRC was proposed. The following conclusions are obtained by modeling and simulation:

1. This paper revealed the mechanism of virtual impedance for improving the stability of grid-forming converter from the perspective of power coupling, and the influence of the virtual impedance on
sub synchronous oscillation was analysed by the sequence impedance model

(2) The analysis results show that increasing the virtual inductance will enlarge the negative damping interval, which is not conducive to system stability. And increasing the virtual resistance can greatly reduce the negative damping interval and improve system stability. However, increasing virtual resistance continuously will deepen the power coupling degree and cause a new power oscillation. Therefore, there are limitations in suppressing the sub synchronous oscillation for grid-forming D-PMSG in weak grid by changing the virtual resistance.

(3) To solve the problem, a dynamic voltage compensation control method based on ADRC was proposed. The ADRC controller parameters were designed by the bandwidth method, which can suppress the sub synchronous oscillation in a certain frequency range and show strong adaptability and good system robustness in weak grid.

Appendix

The output voltage, output current, and filter inductor current of phase A are expressed as follows:

\[ \begin{align*}
V_a(t) &= V_1 \cos(\omega_1 t) + V_p \cos(\omega_p t + \varphi_p) + V_{p2} \cos(\omega_{p2} t + \varphi_{p2}), \\
i_a(t) &= I_1 \cos(\omega_1 t + \varphi_1) + I_p \cos(\omega_p t + \varphi_p) + I_{p2} \cos(\omega_{p2} t + \varphi_{p2}), \\
i_{a2}(t) &= I_L \cos(\omega_L t + \varphi_L) + I_{p2} \cos(\omega_{p2} t + \varphi_{p2}).
\end{align*} \]  

(A.1)

The frequency domain expression of (A.1) can be written as

\[ \begin{align*}
V_a[f] &= \begin{cases} 
V_1, f = \pm f_0, \\
V_p, f = \pm f_p, \\
V_{p2}, f = \pm (f_p - 2f_0), \\
I_1, f = \pm f_0, \\
I_p, f = \pm f_p, \\
I_{p2}, f = \pm (f_p - 2f_0), \\
I_{a2}, f = \pm f_0, \\
I_{p2}, f = \pm f_p, \\
I_{p2}, f = \pm (f_p - 2f_0),
\end{cases} \\
I_a[f] &= \begin{cases} 
I_1, f = \pm f_0, \\
I_p, f = \pm f_p, \\
I_{p2}, f = \pm (f_p - 2f_0),
\end{cases} \\
I_{a2}[f] &= \begin{cases} 
I_L, f = \pm f_0, \\
I_{p2}, f = \pm f_p, \\
I_{p2}, f = \pm (f_p - 2f_0),
\end{cases}
\]  

(A.2)

Frequency domain expressions of system output voltage and current in \( \alpha \beta \) axis reference frames are expressed as follows:

\[ \begin{align*}
V_{a[f]} &= \begin{cases} 
V_1, f = \pm f_0, \\
V_p, f = \pm f_p, \\
V_{p2}, f = \pm (f_p - 2f_0),
\end{cases} \\
V_{\beta[f]} &= \begin{cases} 
\mp V_1, f = \pm f_0, \\
\mp V_p, f = \pm f_p, \\
\mp V_{p2}, f = \pm (f_p - 2f_0),
\end{cases} \\
I_{a[f]} &= \begin{cases} 
I_1, f = \pm f_0, \\
I_p, f = \pm f_p, \\
I_{p2}, f = \pm (f_p - 2f_0),
\end{cases} \\
I_{\beta[f]} &= \begin{cases} 
\mp I_1, f = \pm f_0, \\
\mp I_p, f = \pm f_p, \\
\mp I_{p2}, f = \pm (f_p - 2f_0).
\end{cases} 
\]  

(A.3)

According to the trigonometric function relationship, (A.5) can be obtained.

\[ \begin{align*}
\cos \theta &= \cos \left( \theta_0 + \Delta \theta \right) = \cos \theta_0 \cdot \sin \theta_0 \cdot \Delta \theta, \\
\sin \theta &= \sin \left( \theta_0 + \Delta \theta \right) = \sin \theta_0 + \cos \theta_0 \cdot \Delta \theta.
\end{align*} \]  

(A.5)

Applying the Laplace transform to (A.5), the trigonometric function can be written as

\[ \begin{align*}
\sin \theta[f] &= \frac{1}{2} e^{j \omega_0 f} f = \pm f_p, \\
\cos \theta[f] &= \frac{3M(s) e^{j \omega_0 f}}{2\omega_0} (V_{1L}^* + V_p^* I_p^* + V_{p2}^* I_{p2}^*) = \pm (f_p - 2f_0). 
\end{align*} \]  

(A.6)

The expression of the Park transformation matrix is...
expressed as follows:

\[
T(\theta) = \begin{bmatrix}
\cos \theta & \cos \left(\theta - \frac{2\pi}{3}\right) & \cos \left(\theta + \frac{2\pi}{3}\right) \\
-\sin \theta & -\sin \left(\theta - \frac{2\pi}{3}\right) & -\sin \left(\theta + \frac{2\pi}{3}\right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  

(A.8)

The Park transformation matrix is linearized as follows:

\[
T(\Delta \theta) = T(\theta_0) - T(\theta) \Delta \theta
\]  

(A.9)

where \(\Delta \theta\) and \(T(\theta_0)\) are perturbation component and fundamental component, and the matrix expressions are given as follows:

\[
T(\Delta \theta) = \begin{bmatrix}
1 & \Delta \theta & 0 \\
-\Delta \theta & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(A.10)

\[
T(\theta_0) = \begin{bmatrix}
\cos \theta_0 & \cos \left(\theta_0 - \frac{2\pi}{3}\right) & \cos \left(\theta_0 + \frac{2\pi}{3}\right) \\
-\sin \theta_0 & -\sin \left(\theta_0 - \frac{2\pi}{3}\right) & -\sin \left(\theta_0 + \frac{2\pi}{3}\right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  

(A.11)

Inductance current frequency domain expression can be obtained as

\[
I_{Ld}[f] = \frac{I_L \cos (\varphi_{\text{vir}} - \varphi_{Ld})}{s(J + D)\omega_0} [V_{I_p}^2 + V_{P}I_{I_p} + V_{I_p}I_{p2} + V_{p2}I_{I}], + I_{Lp}e^{j\omega_f} + I_{Lp2}e^{j\omega_f}, f = \pm (f_p - f_0),
\]  

(A.12)

\[
I_{Lq}[f] = \frac{-I_L \sin (\varphi_{\text{vir}} - \varphi_{Ld})}{s(J + D)\omega_0} [V_{I_p}^2 + V_{P}I_{I_p} + V_{I_p}I_{p2} + V_{p2}I_{I}] + jI_{Lp}e^{j\omega_f} \pm jI_{Lp2}e^{j\omega_f}, f = \pm (f_p - f_0).
\]  

(A.13)

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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