Power Supply Control Strategy for Offshore Wind Ship

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Abstract: The electric load of the ship at the bottom berth of the floating offshore wind farm platform is compatible with the power generation of the wind farm generator. The 60Hz ship power and 50Hz wind power adopt frequency conversion, the 50Hz ship power and the 50Hz wind power use the inverter to smoothly switch seamlessly, and the seamless power supply ensures that the ship can be easily and quickly berthed in a short period of time. Based on the inverter power supply control strategy of virtual synchronous generator (VSG) control and grid-connected working mode and autonomous mode of the system small-signal model, the VSG has the characteristics of fast tracking and certain mechanical and electrical inertia compared with the frequency variation of the inverter power supply based on the droop control. Meanwhile, the grid-connected pre-synchronization process and the synchronous generator pull-in synchronization process have similar characteristics, and the frequency and voltage change amplitude are relatively flat. The simulation analysis and experimental results verify the correctness of the control strategy.

1. Introduction
According to the current development status of floating offshore wind farms at home and abroad [1] and the research results of large-scale floating platform stability and the latest wind power technology application results, the ship berthing seamless shore-electric technology and the wind farm power supply are organically integrated. The triangular super-large anti-stage floating wind farm ship is berthed by the wisdom seamless power supply platform. Through the platform to increase the docking of large cruise ships and the use of the platform as a leisure place, etc., thereby improving the economic and social benefits of offshore wind power generation.

The platform ship can be powered by inverter dual output seamlessly, that is, the 60Hz ship adopts frequency conversion power supply, and the 50Hz ship uses inverter to directly supply power. In this paper, the rotor motion equation of synchronous generator (SG), primary frequency modulation characteristics and reactive power regulation delay characteristics are introduced into the control algorithm of inverter power supply. Meanwhile, a new virtual synchronous generator (VSG) control method is proposed. Different settings of the inertia time constant, damping coefficient and delay time constant can better simulate the different characteristics of the synchronous generator. Based on proportional (P), proportional integral (PI) and proportional resonant (PR) controllers, we propose a PR controller with better tracking sinusoidal signal so as to improve the response speed of the voltage-current inner loop controller and better simulate the characteristics of the synchronous generator. In addition, the small-signal model of the inverter power supply under the two working modes of grid-connected and autonomous operation is established, and the influence of relevant parameters on the stability and dynamic response of the VSG control algorithm is analyzed. Finally, a
Matlab/Simulink simulation model and experimental platform based on VSG control are built to verify the theoretical analysis.

2. Wisdom seamless power supply platform of Anti-typhoon floating wind farm ship berthing

According to the dynamic power generation control of wind generators and the seamless power supply of ships, a wisdom information center platform is formed. In high winds, the generator's electrical energy is seamlessly supplied to the berthing ship, thus generating major economic benefits. At the same time, the energy storage is carried out by the energy storage station, and part of the remaining electrical energy is transported to the onshore power grid through the submarine cable \(^2\). When the wind power is small, the energy storage power station first supplements the electric energy and supplies seamless power to the berthing ship. At the same time, onshore power stations supply low-cost electricity to berthing ships and replenish electric energy to energy storage stations. The wisdom information platform realizes free control of the system through cloud computing big data. Wireless information integrates power control with platform recreation management and ship berth management to achieve all-round intelligent information control.

Figure 1 is a wind power floating platform. Wind farm wind power generation is adapted to the number of ships at the bottom berth of the platform and the electric load to the wind farm generator. In moderate air volume, the power consumption of all docked ships is equal to the wind power generation; in high winds, excess electric energy is transmitted to the road power station through submarine cables; in the no wind and windy season, the shore power stations feed electric energy to the wind farm through submarine cables.

![Figure 1. Wind power floating platform](image1.jpg)

Figure 2 is the platform intelligence information center. The small fishing boat berth adopts the voltage envelope to control the seamless connection through the bottom point; the general ship can adopt the inverter double output seamless connection, the 60Hz ship power and the 50Hz wind power adopt the frequency conversion smooth switching seamless connection, 50Hz ship power and 50Hz wind power use the inverter to over-smoothly switch seamlessly and then cut the inverter directly. Seamless power supply ensures that the ship can be easily and quickly berthed in a short period of time, so that wind power can be utilized to the maximum benefit.

![Figure 2. Platform Intelligence Information Center](image2.jpg)
3. Inverter power control strategy

The offshore floating triangular platform wind power supplies seamlessly to the berthing ships. In this paper, the inverter power supply control strategy is used as a wind power platform to model and simulate the power supply to the ship, and it is demonstrated through experiments. Considering the particularity of ship synchronous generator power supply and grid connection, wind power inverter power supply uses virtual synchronous generator (VSG) \cite{3-6} to connect with ship synchronous generator and transfer load. The wind power inverter supplies power to the ship load and the wind power inverter virtual synchronous generator adopts an autonomous strategy.

3.1. Inverter unit main circuit structure and control

The overall control strategy of the inverter power supply based on VSG control is shown in Figure 7.

![Overall control diagram](image)

In Figure 3, S1 ~ S6 are IGBT switch tubes; R, L and C are filter inductor internal resistance, filter inductor and filter capacitor respectively; I1, I2 and I3 are the three-phase circuit of filter inductor output, filter capacitor and flowing to the ship grid busbar; \(U_c\) is the three-phase voltage of the filter capacitor, that is, the busbar terminal voltage of the ship power system; \(P_{ref}, Q_{ref}\) are the active power and reactive power set value; \(P_z\) and \(Q_z\) are the active power and reactive power measurement values of the inverter unit; \(E\) and \(\phi\) are the reference voltage amplitude and phase angle obtained by the VSG control algorithm; \(U_{an}, U_{bn},\) and \(U_{cn}\) are three-phase voltage reference values obtained by the upper VSG control unit; \(M_a, M_b,\) and \(M_c\) are three-phase modulated waves obtained by inner loop control.

The VSG-based inverter power control method mainly includes the outer ring new VSG control and the inner ring PR control. After the instantaneous voltage value of the reference voltage is obtained by the upper layer VSG control, the bottom layer control obtains the modulated wave by the voltage and current double loop control, and then generates a pulse by the Sinusoidal Pulse Width Modulation (SPWM) to drive the on/off of the switch tube.

3.2. System small signal model [7]

Since the proposed control algorithm can work in the grid-connected and autonomous modes of Figure 4, a small-signal model is established respectively. Figure 11 shows that the equivalent circuit in two modes of operation. Among them, the output voltage of the inverter power supply is \(E\) \(\phi\); the busbar voltage of the ship power system is \(U_b\), 0, that is, the busbar voltage of the ship power system is taken as the reference point; \(R_1+jX_1\) is the line impedance; \(Z_L\) is the load impedance.
3.2.1. Grid-connected working mode

The apparent power output of the inverter power supply is:

\[ S = \hat{E}_l = P + jQ = \frac{R_L U_L \cos \varphi - R U_1^2 + X E L \sin \varphi}{R_L^2 + X_L^2} + j \frac{-X E L \cos \varphi + X U_1^2 + R E L \sin \varphi}{R_L^2 + X_L^2} \]  

In the grid-connected mode, the small-signal model of active power and reactive power transmission is:

\[ \Delta P = \frac{\partial P}{\partial \varphi} \Delta \varphi + \frac{\partial P}{\partial E} \Delta E = \frac{-R E L \sin \varphi + X E L \cos \varphi}{R_L^2 + X_L^2} \Delta \varphi + \frac{R U_1^2 \cos \varphi + X U_1^2 \sin \varphi}{R_L^2 + X_L^2} \Delta E \]  

(1)

\[ \Delta Q = \frac{\partial Q}{\partial \varphi} \Delta \varphi + \frac{\partial Q}{\partial E} \Delta E = \frac{X E L \sin \varphi + R U_1 \cos \varphi}{R_L^2 + X_L^2} \Delta \varphi + \frac{-X U_1 \cos \varphi + R U_1 \sin \varphi}{R_L^2 + X_L^2} \Delta E \]  

(2)

(3)

In the grid-connected mode, there are \( \omega_L = \omega_{\text{ref}} \), and the small-signal model of the new VSG control strategy with simultaneous equations (3) and (4) is:

\[ \begin{bmatrix} s(2\tau_L s + \beta) \Delta \varphi = -\Delta P \\ s(1 + T_s) \Delta E = -[k_q (s + T_s) + k_p s + K] \Delta Q \end{bmatrix} \]  

(4)

Set\( X_1 = (\Delta \varphi', \Delta E', \Delta \varphi, \Delta E)^T \), according to equations (9) ~ (11), the small-signal model of the inverter power supply based on the new VSG control in the grid-connected mode is:

\[ X_1' = \begin{bmatrix} -\frac{\beta}{2\tau_L} & 0 & -\frac{\partial P}{\partial \varphi} / \partial E & -\frac{\partial P}{\partial E} / \partial E \\ -\frac{d_1}{\tau_L} & -\frac{d_2}{\tau_L} & -\frac{e}{\tau_L} & -\frac{d_3}{\tau_L} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} X_1 \]  

(5)

Among them:

\[ c = T_s + k_q T_s \frac{\partial Q}{\partial \varphi} / \partial E \quad d_1 = (k_q + K_p) \frac{\partial Q}{\partial \varphi} / \partial E \quad d_2 = (k_q + K_p) \frac{\partial Q}{\partial \varphi} / \partial E \quad d_3 = K_q \frac{\partial Q}{\partial \varphi} / \partial E + k_q T_s \frac{\partial P}{\partial E} / \partial E \quad d_4 = K_q \frac{\partial Q}{\partial \varphi} / \partial E \quad d_5 = K_q \frac{\partial Q}{\partial \varphi} / \partial E + k_q T_s \frac{\partial P}{\partial E} / \partial E \quad d_6 = K_q \frac{\partial Q}{\partial \varphi} / \partial E \]

3.2.2. Autonomous mode

It is assumed that the load is resistive. For convenience of derivation, assuming that the line impedance and the load impedance are combined to be \( R + jX \), the apparent power output of the inverter power supply is

\[ S = \frac{U^2}{Z} = \frac{R E L (\cos^2 \varphi - \sin^2 \varphi) + 2 X E L \sin \varphi \cos \varphi}{R^2 + X^2} + \frac{2 R E L \sin \varphi \cos \varphi - X E L (\cos^2 \varphi - \sin^2 \varphi)}{R^2 + X^2} \]  

(6)

The small signal model of active power and reactive power in the autonomous mode is

\[ \Delta P = \frac{\partial P}{\partial \varphi} \Delta \varphi + \frac{\partial P}{\partial E} \Delta E \]  

(7)

\[ \Delta Q = \frac{\partial Q}{\partial \varphi} \Delta \varphi + \frac{\partial Q}{\partial E} \Delta E \]  

(8)
In this mode of operation, \( \omega_L = \omega \), and reactive power - voltage is used by droop control, then

\[
\left(\omega_{\text{set}} - \omega_L\right) - \frac{1}{k_\omega} + P_{\text{set}} - P_L = \frac{1}{2\tau_S} = \omega
\]

\[
E = E_i - k_\delta Q_s
\]

(9) (10)

According to the simultaneous equations (14) to (17), the small signal model of the inverter power supply in the autonomous mode is

\[
X_2 = \begin{bmatrix}
\frac{1}{2\tau}, & \frac{\partial P}{\partial \phi} & \frac{\partial P}{\partial E} \\
-\frac{1}{\tau}, & 0, & 0 \\
\frac{\partial Q}{\partial \phi}, & 0, & 0
\end{bmatrix} \frac{\partial Q}{\partial E} \left( \Delta \phi, \Delta \phi, \Delta E \right)^T
\]

(11)

4. Simulation and simulation experiments

4.1. Simulation analysis

Figure 5. Output frequency of the grid pre-synchronization process system

Figure 5 shows the output frequency of the grid-connected pre-synchronization process system. In Fig. 5(b), after closing, the switching control strategy is based on the inverter power frequency of the droop control, and during the pre-synchronization \(^8\), the frequency change rate is large, and the synchronous generator frequency change is relatively gentle. In Fig. 5(a), after closing the switch is actuated, the VSG frequency is relatively gently decreased with respect to the inverter power frequency change based on the droop control. At the same time, the synchronous generator frequency increases, and the dynamic frequency of the two frequencies is relatively uniform.

Figure 6. Voltage output response of the grid-connected pre-synchronization process

In Fig. 6(a), during the grid-connected pre-synchronization process, the inverter power supply \(^9\) based on the droop control has a sudden change in the output frequency of the power supply due to the absence of inertia, so the rate of change of the phase difference is large. However, the phase difference between the VSG and the synchronous generator system is attenuated in the positive and negative intervals, and the attenuation amplitude is relatively flat. The simulation results are consistent with the theoretical analysis. Correspondingly, in Fig. 6(b), the envelope of the inverter power source and phase-A voltage difference of synchronous generator system has the same trend with as the phase difference curve. Fig. 7(b) is a partial enlarged view of Fig. 7(a). In the figure, the inverter power
supply based on the droop control has a large change rate of the output voltage during the pre-synchronization of the grid, and the amplitude of the VSG output voltage changes relatively gently.

![Figure 7. Inverter voltage amplitude of the grid-connected pre-synchronization process](image)

The simulation results show that the VSG has the characteristics of fast tracking before the closing switch is operated. At the same time, it has certain mechanical and electrical inertia, and the frequency and voltage change range is relatively flat. The grid-connected pre-synchronization process has similar characteristics to the synchronous generator in the pull-in synchronization process.

### 4.2. Simulation experiment

![Figure 8. Actual measured waveform](image)

Fig. 8(a) shows the distortion condition of the measured waveform of the 6 KW load when the generator supplies 60 Hz, 3 KW + 1 KVar load. The distortion is 50% of the amplitude, which indicates that the V/f control of the generator is poor; Figure 8(b) shows the actual measured waveform of the 6KW load when the inverter supplies power to the 60Hz, 3KW+1KVar load. There is a small amount of fluctuation in the three-phase voltage close to the peak point, and the fluctuation amount is 10% of the amplitude, which indicates that the strategy control has great advantages.

### 5. Conclusion

The ship connected to the platform wind power uses a platform to control the operation of the micro-grid and seamless switching strategy. Without the traditional synchronization table or current limiting control docking, the platform control inverter realizes the power supply docking and port power supply control of the port. And it does not change the structure of the ship power station or basically control the operation of the ship power station. At the same time, the platform control inverter uses the original platform wind power box and cable to achieve fast, convenient and reliable low-voltage continuous electrical connection platform wind power. An inverter device is used to continuously connect the platform wind power to ships of two frequencies. The platform controls the 60Hz inverter to supply power. The 50Hz inverter transition can achieve smooth control and fully utilize the 60Hz power supply inverter, while the direct power supply of the transformer can reduce the loss of the inverter and extend the service life of the inverter.

The electric load of the ship at the bottom berth of the floating offshore wind farm platform is compatible with the power generation of the wind farm generator. The 60Hz ship power and 50Hz wind power adopt frequency conversion, the 50Hz ship power and the 50Hz wind power use the inverter to smoothly switch seamlessly, and the seamless power supply ensures that the ship can be easily and quickly berthed in a short period of time. The SG's rotor motion equation and primary...
frequency modulation characteristics, reactive voltage regulation and reactive power delay characteristics of the VSG control strategy are used to better simulate the characteristics of synchronous generators, which can work in both grid-connected and autonomous modes. VSG has the characteristics of fast tracking and it has certain mechanical and electrical inertia. Meanwhile, the frequency and voltage change range is relatively flat and the grid-connected pre-synchronization process has similar characteristics to the synchronous generator in the pull-in synchronization process.

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References:
[1] Zhang Kaihua, Chen Yunqiao. Review of the deep sea wind farm platform[J]. Solar Energy 2018, (06): 17-18+40.
[2] Xu Jin, Jin Yi, Hu Congchuan, Xiong Chunwei, Zhang Guangzhou, Li Xiaochun. Research on Combined Power Transmission Scheme for Offshore Wind Farm Cluster[J]. Power System and Clean Energy, 2016, 32(11): 107-113.
[3] Liu J, Miura Y, Ise T. Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators[J]. IEEE Transactions on Power Electronics, 2016, 31(5): 3600-3611.
[4] Torres LMA, Lopes LAC, Moran TLA et al. Self-tuning virtual synchronous machine: a control strategy for energy storage systems to support dynamic frequency control[J]. IEEE Transactions on Energy Conversion, 2014, 29(4): 833-840.
[5] Alipoor J, Miura Y, Ise T. Power system stabilization using virtual synchronous generator with alternating moment of inertia[J]. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2015, 3(2): 451-458.
[6] Cheng Chong, Yang Huan, Zeng Zheng et al. Rotor inertia adaptive control method of VSG[J]. Automation of Electric Power Systems, 2015, 39(19): 82-89 (in Chinese).
[7] Meng Jianhui, Wang Yi, Shi Xinchun, Fu Chao, Li Peng. Control Strategy and Parameter Analysis of Distributed Inverters Based on VSG[J]. Transactions of China Electrotechnical Society, 2014, 29(12): 1-10.
[8] Wang Ke, Wang Zezhong, Chai Jianyun, You Rui, Gan Shengfei. Analysis of Grid-connecting Pre-synchronized Process for Synchronously Controlled Inverter Power Source, 2015, 39(12): 152-158.
[9] Guerrero J M, Mukil C, Lee Tzung-Lin, et al. Advanced control architectures for intelligent microgrids—Part I: decentralized and hierarchical control[J]. IEEE Transactions on Industrial Electronics, 2013, 60(4): 1254-1262.