Strategies for Inverter Dual-output Shore-to-ship Seamless Power Supply

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Abstract: This paper simulates the micro-grid to establish a shore-to-ship seamless connection power supply system and control strategy by the shore-controlled inerter dual-output. The shore-controlled 60Hz inverter power supply and the 50Hz inverter transition transformer are directly supplied without changing the control of the ship power station. The shore-ship power supply is seamlessly connected through the shore-controlled inerter, which is suitable for most ships. The strategies for inverter dual-output shore-to-ship seamless power supply are: V/f control method controls inverter constant frequency constant voltage power supply; P/Q control method controls shore ship seamless connection and smooth transfer load; Phase-locked loop control method controls phase-shifting and variable-frequency control of the shore power during the integration of shore power into the ship's power to complete the parallel condition, assisting to stabilize the frequency and voltage of the output of the rectifier inverter; Inverter control reduces frequency and voltage fluctuations of V/f control and P/Q control conversion by following from state following to reverse state following innovation.

1. Introduction

Ships connected to shore power can achieve ship energy conservation and port emission reduction and environmental protection. Taking a ferry between Poland and Sweden in 2012 as an example, it stops at the Polish port for 3 hours every day and stops at the Swedish port for 7 hours. Relative to the cost of power generation/shore power, Sweden and Poland are 724/356 US dollars and 1759/678 US dollars respectively. Save $1,449 per day with shore power. The consultation report of MariTerm AB pointed out that the indirect cost of heavy diesel emissions and noise from shipbuilding power generation in EU countries is more than 10 times the direct cost. If 80% of our ports are connected to shore power by port, the annual energy-saving economic benefits can reach more than 2.1 billion China Yuan, and the social benefits of port environmental protection are more significant. Most of the terminal power installations in China use 400V/50Hz power supply, and most of the ships those use the electric system are not willing to receive shore power because the general ship adopts the method of first stopping the ship and then connecting the shore power and first breaking the shore power to restart the marine generator. Many equipment on the ship is in trouble after power-off. It takes 4 hours to reset after the power is cut off, which affects the sailing of the ship. And there is a danger of simultaneous start after power failure of standby equipment in the engine room. In addition, relatively short time for large ships to dock, it is difficult to calculate and pay electricity charges. An investigation into the captain/chief engineer of an ocean-going ship confirmed that he was unwilling to receive shore electricity within 48 hours of berthing. According to the statistics of the international maritime organization, more than 60% of international shipping ships adopt 460V/60Hz power system, while over 60% of onshore power supply is 400V/50Hz.
power system. The control difference between ship power station and generator is very big, which causes great technical difficulties for the seamless docking of shore ships.

The marine shore power supply system commonly used at home and abroad belongs to the first-stop ship generator and the shore power, and the power-off shore power system of the ship generator is started after the bank power is first broken. The AC system for ships in various countries (except special ships) is basically three-phase AC 460V/60Hz, 400V/50Hz and three-phase AC 6.6 kV/ 60Hz[1]. Therefore, the existing shore power methods in the world generally include: low-voltage shore power / low-voltage ship power supply, high-voltage shore power / low-voltage ship power supply, high-voltage shore power / high-voltage ship power supply three ways. A ferry in Poland and Sweden uses a high-voltage frequency conversion and then a ship-to-shore transformer system, as shown in Figure 1. There are also studies on the use of shore power methods for frequency conversion and different voltage levels of ships [2]. These studies all discuss the energy saving, emission reduction and environmental protection of ship shore power [1-2].

**Figure 1. High voltage variable frequency power supply system diagram for a ferryboat**

This paper simulates the micro-grid to establish a shore-to-ship seamless connection power supply system and control strategy by the shore-controlled inverter dual-output. The shore-controlled 60Hz inverter power supply and the 50Hz inverter transition transformer are directly supplied without changing the control of the ship power station. The shore-controlled power supply is seamlessly connected through the shore-controlled inverter, which is suitable for most ships. The shore-to-ship seamless power supply strategies for the shore-controlled inverter dual-output is proposed and analyzed in Section II. The model device and simulation experiments are obtained in Section III. Conclusion is given in Section IV.

2. **Shore-to-ship seamless power supply strategies for the shore-controlled inverter dual-output**

Figure 2 shows the shore-to-ship seamless power supply strategies for the shore-controlled inverter dual-output. Firstly, the shore power grid lines including the shore power transformer and the rectifier-inverter are respectively electrically connected with the shore power source and the ship power grid, and the shore power grid line is selected as a 50 Hz or 60 Hz line according to the ship power grid standard. The rectifier-inverter adopts an inner loop control method and an outer loop control method, wherein the outer loop control method adopts a V/f control method, and the target frequency of the ship generator is converted into a target frequency of the shore power transformer output, and at the same time, a phase-locked loop control method is used to control the output frequency and voltage of the rectifier inverter. Then, the outer loop control method of the rectifier-inverter is converted from the V/f control method to the P/Q control method to control the ship generator frequency and voltage, and the real-time load power of the ship grid is used as the target power to perform power transfer, so that the output power of the rectifier-inverter increases and the output power of the ship generator decreases. When the ship generator output power drops to the preset power, the ship generator is turned off.
2.1. Outer loop control method

The outer loop control method uses the V/f control method[3] to convert the target frequency of the ship generator to the target frequency of the shore power transformer output. The V/f control consists of a current inner loop and a voltage outer loop[4-5]. The main coefficients are: the current loop proportional coefficient $K_{pi}$ and the integral coefficient $K_{ii}$, the voltage loop proportional coefficient $K_{pv}$ and the integral coefficient $K_{iv}$, let load equivalent resistance $R$, equivalent reactance $X$, filter inductor $L_s$, the rectifier- inverter output current excluding capacitance filter $I_1 \approx I_2 \approx I_d$. $I_d$ and $I_q$ are $dq$ axis components respectively.

Let the $dq$ axis components $U_{dref}$ and $U_{qref}$ of the reference value $U_{ref}$ of the voltage loop be the input, and the $dq$ axis components $V_d$ and $V_q$ of the rectifier-inverter output voltage be the output, and the system equation is the following formula(where $s$ is the integral factor):

$$
V_d = \frac{R K_p K_p s^2 + (R K_p K_p + R K_r K_p) s + R K_r K_p}{L_s s^2 + (K_p + R K_p K_p) s + (K_i + R K_i K_i + R K_p K_p) s + R K_i K_i - U_{dref}} - \frac{L_s X s + X K_p s^2}{L_s s^2 + (K_p + R K_p K_p) s + (K_i + R K_i K_i + R K_p K_p) s + R K_i K_i} I_s
$$

$$
V_q = \frac{-L_s X s + X K_p s^2}{L_s s^2 + (K_p - R K_p K_p) s + (K_i - R K_i K_i - R K_p K_p) s - R K_i K_i} I_s
$$

An A processor is disposed at the second connection end of $L_2$ and the second connection end of $L_3$ to obtain a rectifier- inverter output current value $i_1$, and calculate $dq$ axis components $i_{d1}$, and $i_{q1}$ thereof; A, B processor is disposed between $L_4$ and $R_1$ and a $L_5$ and $R_1$ to obtain the rectifier- inverter output voltage value $v$ and the current value $i_2$, wherein the voltage $v$ includes the $abc$ axis components $v_a$, $v_b$ and $v_c$, then the $dq$ axis component $i_{d2}$, $i_{q2}$ and $dq$ axis components of the voltage $v_d$, $v_q$.

Let $\alpha$, $U_{ref}$, $v_a$, $v_q$ be input, according to V/f control method, the reference values of current loop $i_{dref}$ and $i_{qref}$ are obtained

$$
\theta = \int (2\pi - \alpha) dt, \quad U_{dref} = U_{ref} \cos \theta, \quad U_{qref} = U_{ref} \sin \theta
$$

$$
i_{dref} = K_p (u_{dref} - v_d) + K_i \int (u_{dref} - v_d) dt
$$

$$
i_{qref} = K_p (u_{qref} - v_q) + K_i \int (u_{qref} - v_q) dt
$$
Where, $u_{ref}$ is the voltage loop reference value, according to the voltage setting of the ship's power grid, $\omega$ is the rectified inverter output angular frequency, $\theta$ is the rectified inverter output voltage phase angle.

Let $i_{1d}, i_{1q}, i_{2d}, i_{2q}, i_{dref}, i_{qref}, v_{d}, v_{q}$ be input, according to the inner ring control method, $v_{ad}$ and $v_{aq}$ are obtained, and the specific formula is as follows:

$$v_{ad} = v_{q} - \alpha L_s b_{iq} + K_{p}(i_{dref} - i_{2d}) + K_{i}(i_{dref} - i_{2d})dt$$

(6)

$$v_{aq} = v_{q} - \alpha L_s b_{iq} + K_{p}(i_{qref} - i_{2q}) + K_{i}(i_{qref} - i_{2q})dt$$

(7)

2.2. Phase-locked loop control method

The phase-locked loop control method controls the frequency and voltage of the rectifier-inverter output, and the parallel phase conditions are completed by phase shifting and frequency conversion control of the shore power during the integration of the shore power into the ship power. When the frequency of the input quantity changes, the output of the three-phase phase-locked loop is still the output signal of the same frequency as the input. Three-phase phase-locked loops have good anti-interference ability under the conditions of DC offset, three-phase asymmetry and harmonic distortion. The system has the following formula:

$$v_{q} = V \sin(\theta - \theta_{pll})$$

(8)

$$\theta = \omega_0 t + \theta_0$$

(9)

$$\theta_{pll}(s) = \theta(s) + \frac{(o_{hh} - o_{lb}) + (o_{dd} - o_{db})s}{s^2 + V K_{p_{pll}}s + V K_{i_{pll}}}$$

(10)

Where $\theta$ is the phase angle of the output voltage of the rectifier-inverter, $\theta_{pll}$ is the output of the phase-locked loop, and $o_{hh}$ and $o_{lb}$ are the target values respectively.

Let $v_a, v_b, v_c, o_{hh}$ be input, according to the phase-locked loop control method, the phase-locked loop output $\theta_{pll}$ is obtained. The specific formula is as follows:

$$\theta_{pll} = \int \omega_{pll}dt$$

(11)

$$v_{q} = -\sin \theta_{pll}(2/3v_a - 1/3v_b - 1/3v_c) + \cos \theta_{pll}(\sqrt{3}/3v_b - \sqrt{3}/3v_c)$$

(12)

$$\omega_{pll} = o_{hh} + K_{p_{pll}}v_{q} + K_{i_{pll}}\int v_{q} dt$$

(13)

Where $K_{p_{pll}}$ is the phase-locked loop proportional coefficient, $K_{i_{pll}}$ is the phase-locked loop integral coefficient, $o_{hh}$ is the theoretical angular frequency, and $o_{lb}$ is the angular frequency of the rectifier inverter output voltage.

2.3. V/f control method is converted to P/Q control method

The outer loop control method of the rectifier-inverter, that is, the V/f control method is converted to adopt the P/Q control method[6-7] is adopted. The output power of the device is gradually increased, and the output power of the ship generator is gradually decreased. At the same time, the phase-locked loop control method[8] is used to stabilize the frequency and voltage. In this process, the ship generator can reduce the load by droop control, automatic frequency modulation or manual adjustment of the governor.

P/Q control realizes the maximum utilization of intermittent power supply in the micro-grid, and outputs active and reactive power as their reference values $P_{ref}$ and $Q_{ref}$ respectively. The control principle is: the power reference value is subtracted from the measured value, and the current reference signal $i_{dref}, i_{qref}$ is obtained after the proportional integral controller, thereby controlling the output power of the rectifier-inverter, the proportional coefficient $K_{ip}$ and the integral coefficient $K_{ip}$ of the P/Q control, refer to the following formula:

$$P_{ref} = K_{p_{f}}(f_{ref} - f)$$

(14)
\[ Q_{\text{ref}} = K_{Q1}(U_{\text{ref}} - U) \]  \hspace{1cm} (15)

\[ i_{\text{qref}} = (K_{Pq} + \frac{K_{iQ}}{s})(P_{\text{ref}} + P) \]  \hspace{1cm} (16)

\[ i_{\text{dref}} = (K_{Pd} + \frac{K_{iP}}{s})(Q_{\text{ref}} + Q) \]  \hspace{1cm} (17)

Let \( v_d, v_q, i_{2d}, i_{2q}, P_{\text{ref}}, Q_{\text{ref}} \) be input, according to the P/Q control method, the current loop reference values \( i_{\text{dref}} \) and \( i_{\text{qref}} \) are obtained, and the specific formula is as follows:

\[ P = v_d i_{2d} + v_q i_{2q}, \quad Q = v_q i_{2d} + v_d i_{2q} \]  \hspace{1cm} (18)

\[ i_{\text{dref}} = K_{Pd}(P_{\text{ref}} - P) + K_{iP}\int (P_{\text{ref}} - P)dt \]  \hspace{1cm} (19)

\[ i_{\text{qref}} = K_{Pq}(Q_{\text{ref}} - Q) + K_{iQ}\int (Q_{\text{ref}} - Q)dt \]  \hspace{1cm} (20)

Where \( P_{\text{ref}} \) is the active power reference value, \( Q_{\text{ref}} \) is the reactive power reference value, \( K_{Pp} \) is the proportional coefficient of active control, \( K_{Pq} \) is the proportional coefficient of reactive power control, \( K_{iP} \) is the integral coefficient of active power control, and \( K_{iQ} \) is the integral coefficient of reactive power control.

Let \( i_{1d}, i_{1q}, i_{2d}, i_{2q}, i_{\text{dref}}, i_{\text{qref}}, v_d, v_q \) be input, according to the inner ring control method, \( v_{sd} \) and \( v_{sq} \) are obtained. The specific formulas are as follows:

\[ v_{sd} = v_q - \alpha \omega_{r} i_{1q} + K_{Pd}(i_{\text{dref}} - i_{2d}) + K_{iP}\int (i_{\text{dref}} - i_{2d})dt \]  \hspace{1cm} (21)

\[ v_{sq} = v_q - \alpha \omega_{r} i_{1q} + K_{Pq}(i_{\text{qref}} - i_{2q}) + K_{iQ}\int (i_{\text{qref}} - i_{2q})dt \]  \hspace{1cm} (22)

When the output power of the ship's generator drops to the preset power, the ship's generator is turned off and the power supply is seamlessly switched. Specifically, the rated power of the ship generator with a preset power of 5% can also be set to other sizes according to the situation.

2.4 State following smooth switching control

Figure 3 is the state following smooth switching control[9]. When the shore power is connected to the ship, the phase-locked loop control is synchronized with the V/f control. When the parallel condition is satisfied, the ship power and the shore voltage are the same frequency, the same amplitude, and the same phase. At this time, cut off V/f control and input P/Q control synchronously, and the negative feedback generated by the V/f control disconnection is added to the P/Q control input to effectively reduce the impact amount during the transient voltage and frequency fluctuation, and the simulation and test waveforms are shown in Figure 3.

![Figure 3. State following smooth switching and voltage frequency waveform](image)

3. Model device and simulation experiment

The experimental model includes: two 50Hz/400V/ 20KVA diesel generators, two generator control cabinets and one parallel cabinet, one 60Hz/460V/20KVA diesel generator and control cabinet, two 10KVA multi-function load cabinets, two power cabinets (one 10KVA/380~420V adjustable, one 10KVA/390~480V adjustable), and the inverter is 50Hz/60Hz double output. Using the above V/f, P/Q and phase-locked loop controller, Figure 4 is the schematic structure diagram of the inverter dual-output seamless power supply device. 20KVA/50Hz, 20KVA/60Hz diesel generators simulate different electric ship generators, two 10KVA RL load cabinets simulate ship electrical equipment.
Figure 4. Inverter dual output seamless power supply device principle structure diagram

Experiment 1: 50Hz shore power (with inverter) and 50Hz ship power with the 8KW+3KVar conventional load grid-connected process test.

The phase shift, grid connection and load transfer waveforms are tested as shown in Figure 5. In Figure 5, the yellow sinusoidal waveform (100V/div, 5ms/div) is the ship's input voltage (marked by M) and the blue sinusoidal waveform is the shore inverter output voltage (marked by N); The small square point on M is the phase target value of the ship's power; Then the small square point on N is controlled by the phase-locked loop, and the shore power waveform will be close to the shore power waveform; The phase difference (M and N) is getting smaller and smaller from Figure 5(a),(b) until it is close to 0 as shown in Figure 5(c) (its expansion shown in Figure 5(e)), which is consistent with the grid connection conditions; The phase-locked loop phase shift time of the grid is less than 3s; V/f is simultaneously regulated but the effect of V/f is not obvious because the amplitude of the two voltages is the same.

After the phase-locked loop is phase-shifted and completes the grid connection, the P/Q controller starts to work. After successful grid connection, P/Q control is used to transfer load from ship generator power supply to inverter power supply and the load transfer time is less than 10s. Figure 5(d) shows the short-circuit bypass power supply waveform of the inverter after load transfer, the blue horizontal wave is the inverter output voltage that is 0, the yellow sinusoidal waveform is the ship input voltage and the pink sinusoidal wave with glitch is the load current waveform.
Figure 5. Ship power and shore power integration waveform

Experiment 2: 50Hz shore power (with inverter) and 50Hz ship power with 1KW+4KVar shock load grid-connected process test.

Figure 6. Strong inductive load grid connected waveform

The phase shift, grid connection and load transfer waveforms are tested as shown in Figure 6. In Figure 6(a), the yellow waveform (marked by M) is the ship's input voltage with strong inductive load, which is significantly worse than the normal load as shown in Figure 5(a). The phase difference (M and N) is getting smaller and smaller from Figure 6(a),(b) until it is close to 0 as shown in Figure 6(c). The load transfer is the same as Experiment 1.

Due to the addition of a strong inductive load, the armature reaction of the generator significantly deteriorates the quality of the generator output voltage waveform, with severe distortion at the lowest and highest points (as shown in Figure 6(b)). At this time, in addition to ensuring the same voltage amplitude, the V/f control quickly repairs the distortion waveform. The waveforms of the highest and lowest distortion waveforms before and after the grid connection in Figure 6(c) are not repaired (V/f control does not work) and repaired(V/f control works), respectively.

Experiment 3: 50Hz shore power (with inverter or the generator) and 60Hz ship power with 3KW+1KVar load grid-connected process test.

First case is the generator supplies power to 60Hz ship power with 3KW+1KVar load: Figure 7(a) shows the waveform distortion when sudden addition of 6KW load and the distortion is 50% of the amplitude, which shows that the generator has poor V/f control; Second case is the shore inverter supplies power to 60Hz ship power with 3KW+1KVar load: Figure 7(b) shows the waveform...
distortion when sudden addition of 6KW load and the distortion is 10% of the amplitude, which shows that this strategy V/f control for the inverter has great advantages.

Figure 7. Measured waveform of sudden increase load

4.Conclusions
Ship shore power adopts shore-controlled micro-grid operation and seamless switching strategy. The shore-controlled inverter realizes port power supply docking and port power supply control. It does not need traditional synchronization table or current-limit control docking, and does not change the ship power station structure. The control operation of the ship power station, using the original shore power box and cable, to achieve fast, convenient and reliable low voltage and continuous power shore power. In this paper, a set of inverters is used to achieve continuous powering of shore power for ships of two frequencies (50Hz and 60Hz). 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.

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