Research on Integration Model of Shore-to-ship Power Supply System with High Proportion Renewable Energy

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Abstract. The traditional shore to ship power supply system has been unable to meet the demand of high efficiency and high power quality for warships. Combining with renewable energy and energy storage, this paper studies the integration mode of high proportion renewable energy shore-to-ship power supply system, and proposes three system topologies. According to the demand of 50Hz load power supply, the system topology of DVR scheme is more conducive to improving power supply efficiency, and has grid-connected/islanded function. It not only greatly reduces the dependence on Municipal electricity, improves the reliability and automation, but also realizes the demand of energy saving and environmental protection. Combined with DVR scheme, the control strategy based on inductance current band-pass feedback is proposed to further ensure the high power quality of the load.

1. Introduction

When the warship is in berth, it needs electricity to meet the daily training tasks and the power needs of the crew in daily life. At this time, the use of shore-to-ship power supply has the following advantages:

1) Reducing pollutant emissions. When warships berth, diesel generators are used to supply power. During the combustion process, diesel generates a large number of sulfides and nitrogen oxides, which pollute the surrounding environment. According to the literature[1], the annual total flue gas emission of a single unit with 750 kW power is 49.36 tons.

2) Energy conservation. The power generation efficiency of diesel engine group is low and the cost is high. Using shore-to-ship power instead of diesel engine group can significantly improve the energy efficiency of the wharf, which is in line with the trend of green development.

3) Reduce noise pollution. The vibration and noise of diesel generating units on warships are large when generating electricity, which causes noise pollution. The above effects can be eliminated by using shore-to-ship power, and the life comfort of the crew can be improved[2-5].

At present, most domestic warship terminals are powered by 10kV/400V transformer. Some of them are powered by traditional regulated power supply or simple AC/DC/AC converter[6]. The facilities of
the wharf are relatively simple, which can not meet the needs of the development of warships. The main problems are as follows:

a) Lack of regulated power supply or poor dynamic response performance of regulated power supply. The supply voltage of municipal electric power is susceptible to the influence of load conditions. During the day, the supply voltage is lower at peak power consumption, while at night, the supply voltage is higher at low power consumption. This voltage change of shore-to-ship power may cause damage to electrical equipment of warships, especially transformers and power modules in power supply equipment, and seriously affect the life of normal lighting tubes on warships. Therefore, it is very necessary to set up a stabilizer for shore-to-ship power supply.

b) Reliability depends solely on Municipal electricity. As mentioned above, the reliability of power supply depends solely on municipal power supply, whether directly supplied by municipal power or supplied by traditional voltage regulators. Moreover, currently only one channel power supply is used, and the overall reliability of shore-to-ship power supply is difficult to guarantee. Therefore, further research is needed in energy storage, new energy generation and high-voltage/low-voltage multi-channel power supply[7,8].

In recent years, new energy generation and energy storage technology has made rapid development. Wind power and photovoltaic power generation price have approached or reached the level of municipal electricity, and their reliability has reached a very high level, which is easier to meet the needs of military applications. In ocean power generation, great progress has been made in wave and tidal power generation. Wave energy has achieved stable output of tens of kilowatt, while tidal energy of hundreds of kilowatt has reached a practical level, and is suitable for the application of offshore environment such as military harbor. In terms of energy storage, lithium batteries have been widely used in power storage. Power storage devices such as supercapacitors have also been widely used[9].

In view of the above problems and the development trend of new energy generation and energy storage technology, this paper proposes three kinds of integrated shore-to-ship power supply system topologies with high proportion new energy access, realizes multi-channel power supply of new energy and energy storage, and simultaneously has the functions of seamless switching of grid-connected and islanded mode, integration of high and low voltage, fast dynamic response and so on. The new shore-to-ship power supply system improves efficiency and meets the era requirement of energy saving and environmental protection.

2. DC Convergent Multiport Conversion Scheme

With the popularization of new energy generation technology, the application of renewable energy such as wind power and photovoltaic energy in shore-to-ship power supply system can better improve the power supply efficiency of the system. At the same time, the shore-to-ship power supply may have 380V power supply or 10kV power supply. Considering the integration of high and low voltage power supply and the access of renewable energy, a DC convergent multi-port conversion scheme is proposed. As shown in Figure 1, the high and low voltage power supply is connected by two AC/DC which are connected to the DC bus. While absorbing/feeding back power from the power grid, the grid-connected points are guaranteed to have high power quality. Considering the system power fluctuation brought by new energy access and the convenience of islanded mode operation, an integrated power supply system with high proportion of renewable energy access is formed by appropriate DC/DC ratio of energy storage.
For the power supply mode shown in Fig. 1, when the power of new energy generation is less than the load power, the power flow chart is shown in Fig. 2 (a). At this time, both high and low voltage power supply can provide active power. The flexible allocation of power supply of two power sources can be achieved and even one source absorbs active power from another power source through the control of two four-quadrant AC/DC converter. When the power generated by new energy is greater than the load power, the power flow diagram is shown in Fig. 2 (b). Similarly, the active power fed back to the two power sources can be flexibly allocated between the two power sources. Flexible grid-connected control can control the power quality of grid-connected points in real time by increasing reactive power when power is returned to the grid. The power quality of grid-connected points is not affected, especially when fluctuating active power is returned. In order to further reduce the impact of inverse power on power grid, the information of other power loads in port can be collected in real time to limit the size of inverse power. The surplus power of new energy generation can be solved by energy storage or restriction of new energy generation.

3. Dynamic Voltage Restorer Multi-Port Converter Scheme

Fig. 1 power supply mode can be extended to 60 Hz power supply for warship load. On the basis of DC bus, the frequency of power supply for warship load is obtained by DC/AC. But in some military or civil applications, the warship load only needs 50Hz power supply, so it can be directly supplied by shore-to-ship power supply without any converters. In view of this application, the scheme of Fig. 1 is improved, and a multi-port converter scheme based on dynamic voltage restorer(DVR) is proposed. As shown in Fig. 3, it is an upgrade scheme corresponding to the traditional voltage regulator. The system output voltage is provided by dynamic voltage restorer, which has the following advantages: (1) Considering that most of the power supply is normal in most of the time, it can realize that most of the power is directly supplied by the city power and the system efficiency is greatly improved; (2) Dynamic voltage restorer can realize the ms-level adjustment of the output voltage, which can improve the power quality based on the municipal power supply.
Fig. 3 Dynamic Voltage Restorer Multi-Port Converter Scheme

For the scheme of dynamic voltage restorer shown in Figure 3, K1 in DVR device is closed when 380V power supply is normal. Ship load is supplied by high and low voltage power through K1. At this time, DVR device works in bypass mode. At the same time, the new energy generation can also supply power for the load after AC/DC1 conversion. Because 380V power supply does not go through the converter device, the rated power supply efficiency is greatly improved. When power quality problems such as temporary rise/sag occur in 380V supply voltage, K1 is disconnected and DVR device is started. The voltage is connected in series between 380V and load through series transformer to ensure stable power supply of ship load. At this time, DVR device works in compensation mode. Since DVR device only provides compensation energy, the capacity of DVR depends on compensation capacity. For example, when the compensation voltage is ±20% of the rated voltage, the capacity of DVR is 20% of the load capacity, and the system cost is greatly reduced compared with that in Figure 1.

The DVR scheme shown in Figure 3 can also work in islanded mode, as shown in Figure 4. When high and low voltage power supply is islanded, the AC/DC connecting to 10kV is blocked, thyristor switch for 380V supply is switched off rapidly, DC bus voltage is stabilized by energy storage DC/DC, and the load energy is provided through AC/DC1 of new energy generation converter. At this time, DVR device can be adjusted to bypass mode or compensation mode, cooperating with AC/DC1 to ensure the quality of power supply for ship load. And the grid-connected mode and islanded mode can achieve good seamless switching.

Fig. 4 Islanded mode of dynamic voltage restorer scheme
The DVR scheme shown in Figure 3 can be further improved by connecting the new energy generation converter and energy storage converter to 380V power supply directly. As shown in Figure 5, this scheme has the figure 3’s advantages of direct supply electricity, high power quality by dynamic voltage restorer, seamless switching between grid-connected and islanded mode. Furthermore, its main advantage is improving the efficiency from the new energy power supply to the municipal electricity and ship load. New energy power generation can be directly supplied to the load through its own converter. It does not need to go through AC/DC1 in Figure 3 and reduces the loss caused by AC/DC converter with fewer power converters.

In view of the power supply scheme shown in Figure 5, the new energy power converter and 380V source simultaneously supply power to the load in the grid-connected mode. AC/DC1 stabilizes the DC bus voltage and ensures that AC/DC3 in the DVR device provides compensation voltage for the load. When the system works in the islanded mode, the thyristor and AC/DC2 are blocked as shown in Figure 4, and the energy storage system AC/DC3 works in the voltage source mode, providing stable voltage and frequency support for the load. Other converters work in the same mode compared with Figure 4. DVR can still work in the bypass mode or compensation mode, cooperating with AC/DC3 to ensure the quality of power supply for ship load.

4. Dynamic Voltage Restorer control strategy

![System block diagram of DVR device](Fig.6_system_block_diagram)

The overall control flow of shore power supply system is described in section 3. This section focuses on the control strategy of DVR device. The control strategy based on inductance current band-pass feedback is proposed to effectively compensate the load voltage. Fig. 6 shows the block diagram of DVR system, which is a single-phase schematic diagram. $V_s$ is the grid voltage; $L_s$ and $R_s$ are the line impedance; $V_1$ and $V_2$ are the primary and secondary side voltages of transformers, and their difference $V_{dvr}$ is the partial compensation voltage in series; $L_i$ and $R_i$ are the loads and $I_i$ are the load current; $L_f$, $R_f$ and $C_f$ are the DVR series filter devices, $V_c$ and $I_c$ are the filter capacitor voltage and current; $L_t$ and $R_t$ are the leakage impedance of transformers; $V_i$ is the leakage impedance of transformers. Series output voltage. Traditional control method uses capacitive current as feedback control. However, capacitive
current can not reflect the magnitude of over-current in series structure. In order to protect DVR from over-current, it is necessary to sample the $L_f$ current of filter inductor, which doubles the number of current sensors. In order to reduce the cost of DVR, the power supply system directly uses the filter inductance current for feedback control. According to Fig. 6, the control block diagram of the system is shown in Fig. 7.

![Fig.7 Block diagram of inductive current feedback system](image)

In Figure 7, $V_2$ is the measured value of the load voltage and $V_2^*$ is the instruction value of the load voltage. Double closed-loop control is carried out through the inner loop of inductance current and the outer loop of the load voltage. Among them, $k_V$ is the proportional coefficient of the voltage loop, $K_C$ is the proportional coefficient of the current loop, $k_i$ is the output gain of the converter. According to figure 7, the transfer function of the system can be obtained as shown in equation (1). According to equation (1), the system bode diagram can be drawn as shown in figure 8. It can be seen that there is a peak gain in the high frequency part of the system at this time. The reason is that the LC resonance of the series partial filter makes the system underdamped and there is a risk of instability, which affects the compensation voltage and the load current.

$$G_V(s) = \frac{V_2(s)}{V_2^*(s)} = \frac{(L_f s + r_f)(nk_i k_i + nk_i)}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + 1}$$  \hspace{1cm} (1)

To solve the underdamped characteristic of LC filter in Figure 6, inductance current feedback is introduced again without increasing the number of sensors, and inductance current is introduced into the modulation wave after passing through the bandpass filter. The transfer function of the band-pass filter is shown in equation (2), where the resonant frequency of the band-pass filter is $\omega_0$, equal to the resonant frequency of the LC, and the quality factor is Q. At this time, the system is shown in Figure 9, and the closed-loop transfer function of the system is also obtained according to equation (3).

$$G_V(s) = \frac{1}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + 1}$$  \hspace{1cm} (2)

![Fig.8 Bode Diagram of Inductive Current Feedback](image)
According to equation (3), the closed-loop transfer function bode diagram of inductance current bandpass filter is drawn. As shown in figure 10, compared with figure 8, the high-frequency resonance component is effectively suppressed without affecting the fundamental component. On the basis of not increasing the number of sensors, the system damping characteristic is effectively improved, and the stability of DVR series voltage compensation is increased.

5. Experimental research
In order to verify the feasibility of shore-to-ship power supply system with high proportion renewable energy, an integrated experimental platform is built according to Fig. 5. The main purpose of the experiment is to realize DVR voltage compensation for load and realize the system's function of grid-connected and islanded mode. Fig. 11(a) shows the experimental waveform when the system is connected to the grid. CH1 is the grid current of phase a, CH2 is the load current of phase a, CH3 is the grid voltage Uab, CH4 is the load voltage Uab. At this time, the grid voltage is rated at 380V. Although DVR works in compensation mode, the compensation voltage is zero, so the waveform of voltage grid and load voltage is the same.
According to Figure 5, AC/DC1 can not only provide compensation energy, but also reactive power for 380V power grid. Figure 11(b) shows the waveform of AC/DC1 providing reactive power. CH1 is load current of phase a, CH2 is AC/DC1 current of phase a, CH3 is grid voltage Uab, and CH4 is load voltage Uab. Although series side compensation voltage is zero, AC/DC1 can be used to provide reactive power for the power grid to ensure that the power factor on the grid side is within the controllable range.

Fig. 12 shows the voltage drop waveform of power grid, in which CH1 is AC/DC1 current of phase a, CH2 is load current of phase a, CH3 is power grid voltage Uab, CH4 is load voltage Uab. When the power grid drops to 300V, the load voltage is still guaranteed to 380V by DVR compensation. AC/DC1 will provide the compensation power at this time. It can also be seen from Fig. 12 that there is no obvious distortion in the load voltage. It shows that the control based on inductance current band-pass can effectively suppress the underdamping of the system and ensure the good compensation of the series part for the load voltage.

Fig. 13 shows the experimental waveform of the system in islanded mode. Among them, CH1 is load current and CH2-CH4 is load voltage of phase abc. At this time, cutting off 380V power supply and providing AC voltage support by AC/DC3, system can still ensure the stable power supply to the load.
6. Conclusions
In view of the technical requirements of high proportion renewable energy access and high power quality power supply in shore-to-ship power supply system, three integrated modes of shore-to-ship power supply system are proposed, and the working principles of each mode are analyzed and compared. Based on the 50Hz shore-to-ship power supply system, a DVR series connection scheme with better system efficiency is proposed, which not only ensures the efficient use of new energy access, but also realizes the stable power supply for ship load, and has the function of grid-connected and islanded mode. For DVR scheme, the control strategy based on inductive current feedback is proposed to further ensure the high power quality of the system to the load. Finally, the feasibility of shore-to-ship power supply system and the effectiveness of DVR control strategy are verified by experiments.

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