Active Phase Fault-Tolerant Control of 12-Phase Permanent Magnet Synchronous Generator Controllable Rectifier System

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Abstract. The multi-phase permanent magnet synchronous generator controllable rectification system has the capability of fault-tolerant operation and high reliability, and is widely used in ship power systems. After a phase loss fault occurs in such a system, the DC current output from each rectifier bridge is unbalanced, and the DC voltage ripple coefficient increases. In this paper, from the perspective of power balance distribution of residual phase windings and the symmetrical operation of the system, the design of fault-tolerant control strategy is carried out with current equalization and DC voltage maintenance as the control target. After detecting the phase loss fault of the generator, the blocking fault corresponds to the trigger pulse of the rectifier bridge connected to the whole set of three-phase windings, and the remaining three rectifier bridges are connected in parallel to provide the DC voltage to the load, and the trigger angle of the remaining three sets of rectifier bridges is adjusted to balance the output DC current of each bridge. The simulation and experimental results of a 100kW 12-phase permanent magnet synchronous generator controlled rectifier system operating under normal, phase loss and fault tolerance conditions are compared and analysed. The designed control method can effectively reduce the DC current imbalance and improve the DC power supply quality.

1. Introduction
The ship integrated power system integrates the power generation system, the power distribution system, the daily load, the propulsion load and the high-energy weapon load, which can realize the flexible deployment of the ship's electric energy and improve the ship's electric energy utilization efficiency. The ship's integrated power system is a new technology developed by the navies of various countries in recent years. It is known as the "third revolution" of ship power, and is the only way for all kinds of high-energy weapons to board the ship [1]. In this system, the power generation module is the core part of the ship's integrated power system and is the power source for all loads, playing a vital role.

At present, the types of generators used in medium voltage DC integrated power systems mainly include: induction asynchronous generators, permanent magnet synchronous generators, electric excitation synchronous generators, and hybrid excitation synchronous generators. In order to improve the power supply quality of the medium voltage DC system, the generator generally adopts a multi-
phase scheme. Among them, the multi-phase permanent magnet synchronous generator has the advantages of high speed, high power density, low vibration noise, etc., and is preferred for the power generation module of the ship integrated power system. The 12-phase permanent magnet synchronous generator rectification system has outstanding advantages such as high power density, small voltage pulsation, high reliability and convenient maintenance. It has been widely used in places such as ship electric propulsion, new energy vehicles, and aircraft power systems that require higher DC power supply quality [2]. Compared with the traditional 12-phase permanent magnet synchronous generator uncontrolled rectifier system, the controllable rectification system has greater control freedom, can actively isolate the fault phase, and can fully exert the potential advantage of 12-phase permanent magnet synchronous generator with poor compatibility and fault operation capability. Therefore, after the damage of the controllable rectification system of the 12-phase permanent magnet synchronous generator leads to various types of phase loss faults, fault-tolerant operation and stable power output will directly affect the reliability of the ship power generation system [3].

Domestic and foreign scholars have conducted research on fault-tolerant control technology of multi-phase motors. The main research objects of foreign scholars are switched reluctance motors and multi-phase permanent magnet synchronous motors [4]. Domestic research has focused on fault-tolerant control of multiphase permanent magnet synchronous motors and induction motors [5]. At present, the fault analysis of multiphase synchronous generator rectifier system mainly involves fault diagnosis of uncontrolled rectifier, generator stator turn-to-turn short circuit [6], DC side sudden short circuit [7], bridge running performance [8] and other calculation analysis [9]. However, there is little research on the lack of compatible error control technology for multi-phase synchronous generator controllable rectification system.

In this paper, the fault-tolerant control technology for the phase-failure of the controllable rectification system of 12-phase permanent magnet synchronous generator is studied with the prototype of the 12-phase permanent magnet synchronous generator phase-controlled rectification system. With current balance and DC voltage maintained as the control target, the adaptive fault-tolerant operation of the phase-failed fault of the controllable rectifier system of the generator is realized, which provides technical support for the intelligent development of the ship's integrated power system.

2. Mathematical model
As shown in Figure 1, the twelve-phase permanent magnet synchronous generator controllable rectification system mainly includes two parts. In the permanent magnet synchronous generator part, the stator adopts a twelve-phase Four-Y shift 15° winding structure, and the winding adopts four sets of three-phase symmetric Y-connection modes which are mutually displaced by 15 electrical degrees, and each set of winding neutral points are independent of each other. In the controllable rectification section, each Y-connected winding is connected to a controllable rectifier bridge, each rectifier bridge is composed of 6 thyristors, and the four rectifier bridge DC outputs are connected in parallel to provide a DC voltage to the load. The controllable rectification system using this connection has the following characteristics, each set of windings is independently controlled, and each set of windings is isolated from each other. When any phase missing phase (specifically, the phase winding open circuit or the thyristor open circuit) is faulty, in order to ensure symmetrical operation, the winding of the phase loss fault may be separately withdrawn; under the premise that the DC bus voltage is constant, the increase of the number of phases can appropriately reduce the phase current, which facilitates the selection of thyristor devices under high power conditions.
Figure 1. 12-phase permanent magnet synchronous generator controllable rectifier system.

The rectifier bridge switching device adopts a half-control device thyristor. When the thyristor is subjected to a forward voltage and has a trigger pulse, it is triggered to be turned on. Therefore, by controlling the timing of the thyristor trigger pulse application, the rectified voltage can be controlled to achieve controlled rectification.

Figure 2. Schematic diagram of thyristor trigger pulse generation.

Figure 2 shows the schematic diagram of the thyristor trigger pulse generation principle. First, the detected line voltage $U_{ab}$ is sequentially subjected to filtering and zero-crossing detection to generate a square wave signal; then, according to the trigger angle, the phase difference between the phase voltage and the line voltage, and the phase delay of the filter, the square wave signal is delayed. Correction, synthesizing the A1 phase trigger pulse signal with a pulse width of 30 degrees; finally, generating other pulse sequences based on the A1 phase trigger pulse.

The generator and the rectifying device are connected by the above connection method, and the DC side voltage is adjustable by controlling the trigger pulse.
Figure 3 shows the rectified output voltage of the 12-phase controllable rectification system under different operating conditions. The first one is the normal operation diagram, the second and third are faulty operations with different trigger angles of 0° and 7.5°.

![12-phase rectified voltage diagram](image)

**Figure 3.** 12-phase rectified voltage diagram.

The positions of the symbols I, II, III and IV in the figure are the corresponding working time zones of the first, second, third and fourth rectifier bridges respectively. During normal operation, the working time zones of the four rectifier bridges are the same, the voltage waveforms are the same, and the size is equal. In the absence of phase failure (the second rectifier bridge exits the power supply), the working time of the first rectifier bridge is extended to the second working time zone, and the average voltage is slightly decreased. Under the condition of constant load, the first rectifier bridge is inevitably caused. The DC current increases significantly, and the DC currents of the rectifier bridges are no longer equal, and the power is no longer balanced, which affects the stable operation of the entire system.

3. Control method

For each set of Y-type 3-phase windings of the stator, since the neutral point is not drawn, there is no zero-sequence current. If a single-phase phase loss fault occurs, the asymmetric operation will generate a negative sequence current, which is difficult to control, thus causing the loss of the motor is increased, efficiency decrease, and temperature rise. To deal with this problem, this paper considers the use of a set of Y-type 3-phase windings that actively isolate the fault phase to avoid adverse effects on the fault-tolerant operation of the generator.

After the 12-phase controllable rectification system has a phase loss (1 set of Y-type 3 phase) fault, the DC voltage ripple increases, and the DC current of each rectifier bridge is no longer balanced, so the fault-tolerant control of the rectifier system under such phase loss faults The trigger angle needs to be adjusted to equalize the DC current of each bridge, and at the same time improve the DC voltage power supply quality.

The twelve-phase controllable rectification system independently controls each rectifier bridge. The key of fault-tolerant control is to balance the DC current output of the remaining three bridges by adjusting the trigger angle corresponding to each rectifier bridge.
Taking the second-phase winding phase loss fault as an example, designing a single-phase three-phase winding without participating in the rectification power supply, the fault-tolerant operation control strategy of the 12-phase permanent magnet synchronous generator rectifier system lacking phase fault, as shown in Figure 4, is fault-tolerant control block diagram.

After the occurrence of phase loss fault occurs, the second set of windings of the fault phase exits the rectification power supply, and the output current of the rectifier bridge corresponding to the remaining three sets of windings is no longer balanced. The purpose of fault-tolerant control is to adjust the trigger angle of the first and fourth rectifier bridges with reference to the output current of the third rectifier bridge, so that the output currents of the remaining three rectifier bridges tend to be the same, and the power of each rectifier bridge is balanced.

4. Experimental verification
In order to verify the effectiveness of the designed control algorithm, a 12-phase permanent magnet synchronous generator phase-controlled rectifier system test platform is built. The main components are shown in Figure 5. The main parameters of the generator are shown in Table 1.
Figure 5. Test platform for controlled rectifier system.

Table 1. Parameters of simulation model.

| Parameter                     | Value   |
|-------------------------------|---------|
| Rated power PN/kW             | 100     |
| DC output rated voltage UdcN/V| 460     |
| Rated frequency fs/Hz         | 400     |
| DC output rated current IdcN/A| 220     |
| Rated speed nN/r/min          | 12000   |
| Polar log p                   | 2       |
| Number of phases m            | 12      |
| Voltage regulation method     | Phased rectification |

Due to the limitation of the test conditions, the generator speed did not reach the rated speed in the actual test. The actual working frequency was 50 Hz, the rotational speed was 1500 rpm, the initial trigger angle was set to 90°, and the load was 4.5 Ω pure resistive load.

Figure 6 shows the test results of the changes in the DC output current of each rectifier bridge after normal operation, phase loss failure, and fault-tolerant control algorithm.

Figure 6. Current of each bridge before and after fault-tolerant control.
Figure 7 shows the changes in DC voltage after normal operation, phase loss failure, and fault-tolerant control algorithm.

![DC Voltage Graphs](image)

**Figure 7.** Fault tolerant control block diagram.

Table 2 shows the test results of the average and unbalanced DC current of each rectifier bridge under three operating conditions.

| Working condition       | Idc1     | Idc2     | Idc3     | Idc4     | Unbalanced degree |
|-------------------------|----------|----------|----------|----------|-------------------|
| Normal                  | 2.90A    | 2.95A    | 2.92A    | 2.88A    | 1.25%             |
| Missing phase           | 5.79A    |          | 3.25A    | 2.74A    | 47.51%            |
| Fault tolerance         | 4.01A    |          | 3.97A    | 4.01A    | 0.77%             |

The pulsation coefficient is one of the important indicators to measure the quality of the rectified voltage. The calculation method of the pulsation coefficient $S_n$ is shown in formula 1.

$$S_n = \frac{\text{Lowest harmonic amplitude}}{\text{DC voltage average}}$$  

Table 3 shows the DC voltage mean and pulsation coefficient after normal operation, phase loss failure, and fault-tolerant control algorithm. After the fault occurs, the DC voltage average is stable, but the power quality is reduced, and the pulsation coefficient is increased. After the fault-tolerant control algorithm, the DC voltage average remains basically unchanged, the pulsation coefficient is reduced, and the power supply quality is improved.

| Working condition       | Normal   | Missing phase | Fault tolerance |
|-------------------------|----------|---------------|-----------------|
| Mean                    | 55.7038V | 55.1479V      | 55.5604V        |
| Pulsation coefficient   | 0.89%    | 4.9%          | 2.18%           |
Under normal operating conditions, the DC current of each bridge is balanced. After detecting the phase loss fault, the second set of windings exits the rectification power supply, the corresponding rectifier bridge DC current becomes zero, and the remaining three bridge currents increase, the first set of windings corresponding to the rectifier bridge output current is the largest, the fourth set The output current of the rectifier bridge corresponding to the winding is the smallest, and the DC current imbalance is 47.51%. After the fault-tolerant control is switched, the output current of the rectifier bridge corresponding to the third and fourth windings is reduced, and the output current of the rectifier bridge corresponding to the first set of windings is increased, and finally the three sizes tend to be uniform, and the DC current imbalance is 0.77%.

5. Conclusion
In this paper, the influence of phase loss (1 set of Y-type 3 phase) fault on the performance of the rectifier system in the controllable rectification system of 12-phase permanent magnet synchronous generator is analyzed. According to the energy balance distribution of the remaining sets of windings, a fault-tolerant control algorithm under such phase loss faults is designed to balance the DC currents of the remaining rectifier bridges. The 100kW 12-phase permanent magnet synchronous generator controllable rectification system was tested. After the phase loss fault occurred in the rectification system, the DC voltage was stabilized by fault-tolerant control, and the residual phase current was balanced, which verified the effectiveness of the control strategy.

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