Research on Grounding Fault of 12-phase Rectifier Generator in Parallel Operation

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Abstract. 12-phase rectifier generators have been widely used in ship power systems, since they can provide high quality DC voltage. In view of the safety and reliability requirements of power supply during ship navigation, the DC side grounding faults of two paralleled 12-phase rectifier generators are studied through theoretical analysis and simulation analysis. First of all, the DC voltage expression of the 12-phase rectifier generator under normal condition is derived. Secondly, the zero sequence circuits of the DC side grounding fault are studied, the DC voltage is calculated by the phasor method, the DC output current of generator is analyzed by the zero sequence circuits. Finally, the correctness of the analysis method is verified by the simulation model.

1. Introduction
The 12-phase rectifier power system has the advantages of high quality DC output voltage, good electromagnetic compatibility and high energy conversion efficiency. It has gradually replaced the traditional DC power supply forms such as DC generators, and has been widely used in independent power systems such as naval integrated power system and aircraft power supply systems [1]. The safety and reliability of the power system are very important in the navigation of ships and aircraft. Therefore, it is necessary to analyze and study the possible faults of the system.

At present, there is a certain foundation for the study of some faults of 12-phase rectifier generators, including sudden short circuit in DC side [2], stator inter turn short circuit [3-4], stator inter phase short circuit [5-6], and bridge missing fault [7]. Grounding fault is the most common fault in the power system, accounting for more than 80% of the total fault [8]. At present, the research on grounding fault at home and abroad mainly focuses on fault location and protection control design of distribution network. Reference [9] analyzes the fault current of single-phase high impedance grounding fault in AC resonant grounding system, and proposes a fault location method based on zero sequence current attenuation periodic component. Reference [10] analyzes the single-phase grounding fault of flexible DC power grid with large-scale wind power access, obtains the expressions of DC voltage and DC current after fault through theoretical calculation, and proposed the fault current limiting method suitable for the system. The study for the grounding fault of generator mainly focus on three-phase AC motor, and the research on grounding fault of multi-phase rectifier generator is less. In reference [11], the neutral point voltage of six-phase rectifier generator after single-pole grounding fault of ship DC bus is simulated and analyzed, and the fault location is realized by wavelet analysis and fractal dimension analysis. Reference [12-13] analyzed the influence of different grounding modes on AC side grounding faults of a single
12-phase rectifier generator. However, for the ship power system, the mode of parallel operation of double power stations is often used to ensure the navigation safety and reliability [14]. The occurrence of grounding fault will affect the parallel operation of the rectifier generator, and even inhibit the conduction of the normal motor rectifier bridge.

Based on the parallel operation of two 12 phase rectifier generators, this paper analyzes the DC side positive grounding fault, establishes the fault equivalent zero sequence circuit, obtains the zero sequence voltage of each generator, calculates the DC side voltage and generator output current, and verifies the correctness of the analysis method through simulation, the phenomena of DC side grounding fault is analyzed.

2. DC voltage analysis of twelve-phase rectifier generator

The 12-phase rectifier generator is composed of synchronous generator and rectifier bridge. Its stator windings are 4 groups of three-phase star-connected symmetrical windings with phase shift of 15° in sequence in space, as shown in Fig. 1. In the figure, \( R \), \( L \) is the line resistance and inductance of the generator stator winding, and \( R_n \) is the grounding resistance. If the initial phase angle of phase A1 is 0, the phase voltage equation of AC side in normal operation is expressed as

\[
\begin{align*}
\bar{u}_{a1} &= U_m \sin\omega t - \frac{(n-1)\pi}{12} \\
\bar{u}_{b2} &= U_m \sin\omega t + \frac{2\pi}{3} - \frac{(n-1)\pi}{12} \\
\bar{u}_{c3} &= U_m \sin\omega t + \frac{2\pi}{3} - \frac{(n-1)\pi}{12} \\
\end{align*}
\]

(1)

Where, \( U_m \) is the peak phase voltage, \( n = 1,2,3,4 \).

As the neutral points of each three-phase AC winding are not connected to each other, affected by the grounding resistance, there is only two-phase conduction on one rectifier bridge at any time without considering the conduction overlap angle, and the DC side voltage is the maximum line voltage of each three-phase winding on the AC side. Therefore, the DC voltage equation is expressed as

\[
\bar{u}_{dc} = \sqrt{3} U_m \sin(\omega t + \frac{\pi}{6} - \frac{k\pi}{12})
\]

(2)

\( \frac{7\pi}{24} + \frac{k\pi}{24} \leq \omega t \leq \frac{3\pi}{8} + \frac{k\pi}{12} \)

Where \( k \) is an integer between 0 and 23.
3. DC side single-pole grounding fault analysis

The ship medium voltage DC power station are usually equipped with different types of generators. Therefore, the parameters of generators in parallel operation will be different. The neutral point of generator G1 on the AC side is grounded through \( R_{n1} \), and the neutral point of generator G2 on the AC side is grounded through \( R_{n2} \). According to reference [14], two generators are set to distribute power according to the ratio of 4:1, and the positive pole of DC side is grounded through the grounding fault resistance \( R_f \). The fault diagram is shown in Figure 2.

**Figure 1.** Schematic diagram of 12-phase rectifier generator

**Figure 2.** Schematic diagram of DC side grounding fault
After the grounding fault occurs, the fault point is equivalent to a fault voltage source, whose amplitude is equal to the negative value of the output positive voltage of the rectifier generator, it is expressed as

$$u_f = -E_+$$  \hspace{1cm} (3)

Where, $E_+$ is the output positive voltage of the rectifier generator, and its value is equal to the maximum positive voltage in the 12-phase voltage at any time. By decomposing the system voltage source into the superposition of normal phase voltage and fault voltage, the equivalent circuit of fault voltage can be obtained, as shown in Figure 3. The phase voltage equation of AC side of each generator after the fault occurs is expressed as

$$u_{xn-f}(t) = u_{xn}(t) + u_f(t) + i_f(t)\cdot R_f$$  \hspace{1cm} (4)

Where, $u_{xn-f}$ is the phase voltage after the fault and $i_f$ is the current at the grounding fault resistance, $x=a,b,c$. The DC voltage after fault is the maximum line voltage on each three-phase winding of the AC side after the fault. The conduction phases of generator at a certain time are set as $x_n$ and $y_n$. The expression of DC voltage can be obtained by formula (4).

$$u_{dc-f}(t) = u_{xn-f}(t) - u_{yn-f}(t) = u_{dc}(t)$$  \hspace{1cm} (5)

It can be seen from equation (5) that the DC side voltage has no obvious change before and after the fault.

![Figure 3. Simplified diagram of zero sequence circuit for DC side grounding fault](image)

The fault point current $i_f$ can be obtained from the fault equivalent zero sequence circuit, and the AC side grounding resistance is equivalent to parallel connection. The generator line resistance $R$ and inductance $L$ can be ignored in the calculation, and their expressions are as follows

$$i_f = \frac{u_f}{R_{n1} + R_f + j\omega L_1 + R_{n2} + j\omega L_2 + R_f}$$

$$\approx \frac{u_f}{\frac{R_{n1}R_{n2}}{4(R_{n1} + R_{n2})} + R_f}$$  \hspace{1cm} (6)
From Kirchhoff’s current law at point K in Figure 2, the following relation can be obtained

\[ i_{g1,f} + i_{g2,f} = i_f + i_{load} \]  

(7)

Where, \( i_{g1,f} \) and \( i_{g2,f} \) are the output current of generator G1 and G2 after fault respectively, and \( i_{load} \) is the load current.

Since the DC side grounding fault will not change the DC side voltage, the DC load current will not change after the DC side fault occurs, G1 and G2 will continue to distribute power in a 4:1 ratio. Therefore, the output current of the two rectifier generators can be expressed as

\[ \begin{align*}
   i_{g1,f} &= \frac{4}{5}(i_{load} + i_f) = i_{g1} + \frac{4}{5} i_f \smallskip 
   i_{g2,f} &= \frac{1}{5}(i_{load} + i_f) = i_{g2} + \frac{1}{5} i_f
\end{align*} \]  

(8)

Where \( i_{g1} \) and \( i_{g2} \) are the output current of generator G1 and G2 in normal operation.

4. Simulation of DC side positive grounding fault

The parallel operation simulation model of two 12 phase rectifier generators is built in this paper. The rated output voltage of the rectifier generator is 4.2kV, the AC side grounding resistance of the generator G1 is 200Ω, the AC side grounding resistance of the generator G2 is 800Ω, and the resistance of DC side is 20Ω. Four groups of grounding fault simulation experiments are set on the DC side of the generator, which are direct grounding fault, grounding fault through 10Ω resistance, grounding fault through 50Ω resistance, grounding fault through 100Ω resistance. The fault is set to occur at 2s. The simulation waveform is shown in Figure 4.

The maximum values of fault point current, G1 output current and G2 output current can be calculated by equation (6) and equation (8) when DC Positive grounding fault occurs. Compared with the maximum values of each current in the simulation, table 1 is obtained as follows.

It can be seen from figure 4 and table 1 that after the DC side grounding fault occurs, the DC voltage amplitude has no obvious change, while the output current of the two generators increases significantly. The simulation results are basically consistent with the calculation results.
Table 1. Current values of different fault resistance under DC grounding fault

| Fault Resistance $R_f$ (Ω) | Calculated value | Simulation value |
|---------------------------|------------------|------------------|
|                           | $I_f$ (A) | $I_{g1,f}$ (A) | $I_{g2,f}$ (A) | $I_f$ (A) | $I_{g1,f}$ (A) | $I_{g2,f}$ (A) |
| 0                         | 60.9      | 217.6          | 54.3          | 60.4      | 215.9          | 54.0          |
| 10                        | 48.8      | 207.9          | 51.9          | 48.4      | 206.1          | 50.6          |
| 50                        | 27.1      | 190.6          | 47.6          | 26.9      | 189.5          | 47.9          |
| 100                       | 17.4      | 182.8          | 45.6          | 17.2      | 181.2          | 46.1          |

5. Conclusion

In this paper, the DC side grounding fault of two rectifier generators in parallel operation with pure resistance load are analyzed theoretically and verified by simulation, and the following conclusions are obtained:

Under the condition of parallel operation of two rectifier generators, there is no obvious fluctuation of DC voltage after DC side grounding fault, the output current of the generator fluctuates. The output current will supply the power to the grounding point and cause the DC output overcurrent. In addition, the fault current of the two generators is distributed according to the power ratio to maintain the stable state of parallel operation.

Therefore, when grounding fault occurs in the parallel system of two rectifier generators, DC side voltage and DC output current can provide reference and basis for fault location.

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