Calculation method of steady-state fault current for offshore wind farm

Miao Weiying1,a*, Gao Houlei1,b, Xu Bin1,c

1Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education, Shandong University, Jinan 250061, China
a*email: 201814270@mail.sdu.edu.cn, bemail:houleig@sdu.edu.cn, cemail:xubin@sdu.edu.cn

Abstract. In order to improve the efficiency of solving the steady-state fault current of the offshore wind farm current collection system, In this method, the equivalent model of the PMSG and the VF control converter is established by taking into account the low-voltage ride-through in the case of failure. The Newton-Raphson method is used to iteratively calculate the fault equivalent network. By establishing a simulation model under PSCAD, the symmetric and asymmetrical faults in the collector system of a grid-connected permanent magnet wind turbine connected to the VSC-HVDC are simulated. Simulation results verify the effectiveness and accuracy of the calculation method.

1. Introduction

Literature [1] established a simplified equivalent model of a single direct drive wind turbine, and proposed a fast simulation method for direct drive wind farms. Literature [2, 3] established a simplified model of a single permanent magnet wind turbine and equivalent it to a constant power current source to calculate the short-circuit fault current of the wind farm. At present, wind turbines generally have low voltage ride-through capability, and the above studies have not considered the situation of low voltage ride-through under fault conditions of permanent magnet wind turbines. Literature [4] established a fault equivalent model for permanent magnet wind turbines and doubly-fed wind turbines, analyzed the mechanism of short-circuit current changes in wind farms during faults, and gave short-circuit current calculation methods for hybrid wind farms.

The above-mentioned studies are all oriented to the fault analysis of AC grid-connected wind farms, and the steady-state fault current solution methods suitable for VSC-HVDC grid-connected offshore wind farms are still lacking. The steady-state fault current solution method is the basis of the design of the relay protection system. Therefore, studying the steady-state fault current calculation method of the offshore wind farm collection system is of great significance to the protection analysis and design of the VSC-HVDC grid-connected offshore wind farm.

2. Offshore wind farm connected to the grid via VSC-HVDC

The structure of the wind farm studied in this paper is shown in Figure 1. The output of the permanent magnet wind turbine is collected through the medium-voltage feeder, collected to the high-voltage cable through the step-up collector transformer, and then sent to the commutation through the secondary boost through the converter transformer on the wind farm side. Finally, it is connected to the grid via the VSC-HVDC transmission system.
2.1. Fault equivalent model of permanent magnet wind turbine considering low voltage ride through

Since permanent magnet wind turbines need to provide support current for reactive power output during the fault period in the wind farm grid connection standard, the d and q axis components of the grid-side converter control reference value of the permanent magnet wind turbine after the fault can be controlled as\(^\text{[5]}\)

\[
\begin{align*}
    i_{d \text{ ref}} &= i_{d0} & 0 \leq i_{d \text{ ref}} & \leq \sqrt{i_{\text{max}}^2 - i_{q \text{ ref}}^2} \\
    i_{q \text{ ref}} &= f \left( u_g \right) = i_{q0} + K_d \left( 0.9 - u_g \right) i_N & K_d \geq 1.5
\end{align*}
\]  

(1)

\(i_{d \text{ ref}}\) and \(i_{q \text{ ref}}\) are the reference values of the active and reactive current output by the converter after the fault; \(i_{\text{max}}\) are the maximum current allowed to flow through the inverter; \(u_g\) are the terminal voltages.

Calculate the initial value of grid-side converter current from the working conditions before the fault \(i_{d0}\) & \(i_{q0}\). Since the converter adopts grid voltage orientation \(^\text{[8]}\), that is \(u_g = u_g\), \(u_q = 0\), the output active power and reactive power can be written as

\[
\begin{align*}
    P_{\text{PMSG}} &= \frac{3}{2} \left( u_{g0} i_{d0} + u_{g0} i_{q0} \right) = \frac{3}{2} u_{g0} i_{d0} \\
    Q_{\text{PMSG}} &= \frac{3}{2} \left( u_{g0} i_{d0} - u_{g0} i_{q0} \right) = -\frac{3}{2} u_{g0} i_{q0}
\end{align*}
\]  

(2)

\[
\begin{align*}
    i_{d0} &= \frac{2 \cdot P_{\text{PMSG}}}{3 \cdot u_{g0}} \\
    i_{q0} &= \frac{-2 \cdot Q_{\text{PMSG}}}{3 \cdot u_{g0}} \\
    i_{g0} &= i_{d0} + j i_{q0}
\end{align*}
\]  

(3)

The terminal voltage of the permanent magnet wind turbine before the fault \(u_g\) is generally near the rated value, and the active and reactive power are determined by the working conditions before the fault. In addition, \(i_{d0}\) & \(i_{q0}\) can be represented by output power and

It can be seen that the steady-state short-circuit current output by the converter is determined by the terminal voltage. So there is
2.2. Fault equivalent model of VSC converter
The VSC wind farm side converter adopts VF control. While stabilizing the voltage and frequency, in order to meet the system power balance, the output current changes greatly, but like the PQ control inverter, there is a limitation of output capacity. There is also the maximum output current, so the VF-controlled converter has a constant voltage working state and a current saturated working state in the event of a collector system failure \[6\].
3. Method for Solving Steady Fault Current of Offshore Wind Farm Collection System

Assuming that a two-phase short circuit occurs at point A of the high-voltage cable, the simplified equivalent diagram after the fault is shown in Figure 2. The boundary conditions are:

\[
\begin{align*}
I_f' + I_f &= 0 \\
U_f' &= U_f
\end{align*}
\] (5)

The composite sequence network can be further simplified as shown in Figure 3, using the mesh current method to solve each equivalent circuit.

According to the above analysis, the wind farm side converter can be approximately equivalent to a voltage source when the position of the obstacle occurrence point is farther than the VF control point. When \( Z_f \) is relatively small and the converter output current exceeds its saturation value when, the converter can be approximately equivalent to a current source.

The iteration idea is as follows: Firstly, the converter is equivalent to the voltage source, and when the output current of the converter exceeds the limit during the iteration process, the converter is equivalently replaced according to the current source.

When \( I_G < I_y \max \),

\[
\begin{align*}
I_{m1}(Z_1 + Z_2) + U_{dg} &= E_G \\
I_{m2}(Z_2 + Z_3) &= U_{dg} \\
I_{m2} - I_{m1} &= I_{dg} = f(u_1)
\end{align*}
\] (6)

When \( I_G > I_y \max \),

\[
\begin{align*}
I_{m1}(Z_1 + Z_2) + U_{dg} &= E_G \\
I_{m2}(Z_2 + Z_3) &= U_{dg} \\
I_{m2} - I_{m1} &= I_{dg} = f(u_1) \\
I_{m1} &= I_G
\end{align*}
\] (7)

Newton Raphson method is used to solve iteratively. During the iterative process, the output voltage amplitude and phase angle of the permanent magnet fan are calculated, and then the d and q axis currents are corrected, and then the phase angle is corrected. Use matlab to write programs to calculate each data. The steps are as follows:

1) Form the correction equation:

\[ f(x) = 0 \]

The correction equation is: \( f(x^{(0)}) = -f^{(0)} \Delta x^{(0)} \). Where: \( f^{(0)} = \left. \frac{\partial f}{\partial x} \right|_{x=x^{(0)}} \).

2) Calculate \( x^{(k)} \) correction amount:
Fig. 3 AB Two-phase short circuit composite sequence diagram
\[ \Delta x^{(k)} = -J^{(K)} \begin{bmatrix} f(x^{(k)}) \end{bmatrix} \theta_{dg} \]
\[ x^{(k+1)} = x^{(k)} + \Delta x^{(k)} \]

3) Iterative calculation:
\[ x^{(k+1)} = x^{(k)} + \Delta x^{(k)} \] \( k=0,1,2,3,4 \ldots \)

During each iteration, the value of \( \theta_{dg} \) must be corrected.

4. Simulation

Construct the power grid model shown in Figure 1, and the equivalent circuit diagram after the fault is shown in Figure 2. The permanent magnet wind farm converter transformer short-circuit impedance is 3%, the single rated capacity is 2MW, and the reactive power gain coefficient is 2. The collector transformer has a short-circuit impedance of 11% and a rated capacity of 200MW. The impedance of R1 is (0.34+j0.85), the impedance of R2 is (0.97+j2.78), and the impedance of R3 is (1.46+j4.15).

Verification of the grid fault analysis method for the above-mentioned permanent magnet direct drive wind farm. Table 1 shows the comparison between the simulated value and the theoretical calculation value of the voltage and current on the system side and the wind farm side when a three-phase short circuit occurs at point A under rated conditions. Table 2 shows the comparison between the simulation value and the theoretical calculation value of the voltage and current of the system side and the wind farm side when the AB phase short circuit occurs at point A under the rated conditions. From the comparison of the calculated and simulated values in Table 1, Table 2, it can be seen that the calculation results of the fault current calculation method proposed in this paper and the simulation analysis results are very close in both symmetric and asymmetric fault conditions. Verify the effectiveness and accuracy of the method proposed in this article.

| Category | Wind farm side voltage (kV) | Wind farm side current (kA) | Grid side voltage (kV) | Grid side current (kA) | Fault point current (kA) |
|----------|-----------------------------|-----------------------------|------------------------|------------------------|-------------------------|
| Calculated | 0.0765∠13.75° | 2.771∠-76.64° | 6.342∠2.56° | 0.874∠-85.29° | 4.255∠-80.18° |
| Simulation | 0.0743∠10.16° | 2.844∠-72.67° | 6.125∠7.67° | 0.919∠-80.30° | 4.324∠-75.86° |

| Category | Wind farm side voltage (kV) | Wind farm side current (kA) | Grid side Voltage (kV) | Grid side current (kA) | Fault point current (kA) |
|----------|-----------------------------|-----------------------------|------------------------|------------------------|-------------------------|
5. conclusion
In this paper, by establishing an equivalent model of permanent magnet direct-drive wind turbines and VSC converters considering low voltage ride-through under fault conditions, using numerical iterative algorithms, a method for solving the steady-state fault current of the offshore wind farm collection system is proposed. The establishment of a simulation model verifies the accuracy of the method, and lays a foundation for analyzing the adaptability of conventional AC protection in the offshore wind farm collection system and proposing protection principles and protection system design schemes suitable for offshore wind farm collection systems.

Acknowledgments
Project supported by the Chinese National Natural Science Foundation(51877127)

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