A Micro-grid Fault Section Positioning Method Based on Fault Steady State Component

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Abstract. After the micro-grid is connected to the distribution network, the unidirectional power flow in the original network is transformed into a bidirectional flow, and the original protection device cannot meet the current safe operation of the micro-grid. Due to the complex structure of the micro-network, it is necessary to study the fault location and identification methods in the network when a fault occurs. In this paper, in order to solve the fault section location problem, the phase-to-phase short circuit model of the micro-grid under the state of distributed power grid-connected faults was established, and the positive sequence currents amplitude at the upstream and downstream of the fault point are extracted using the symmetrical component method. The fault section is determined by the amplitude of the positive sequence current at the adjacent detection point on the fault branch. It solves the problem of increasing the difficulty of fault detection due to changes in the access of conventional power electronic devices and changes in short circuit types. The distribution network model was built by MATLAB to simulate and verify the feasibility of fault-based steady-state component section positioning method.

1. Introduction

At present, with the rapid development of new energy in China, At the same time, the distributed generation technology has the advantages of flexibility and environmental protection, so more and more small-scale micro-grids are put into use in distribution network, which leads to the change of the original trend of the network therefore this mode of operation cannot meet the current safe operation of the power grid.[1-4]

In recent years, domestic and foreign scholars have carried out a lot of research work on the fault characteristics and protection schemes with DG access in the distribution network, and have achieved certain results. For example, in reference [5], a fault zone location matrix algorithm based on master-slave regional pilot protection is proposed to improve the security of the distribution network with a large number of DGs. However, the real-time communication requirements of this method are very high. Reference [6] proposes a centralized and distributed protection method for fault area detection and isolation based on the characteristics of complex distribution networks, and continuously optimizes and improves the operation safety of the power grid. Literature [7] proposes a regional protection scheme based on graph theory and directed graphs. The IED is used to protect the terminal and divide the distribution network into sectors. The information is processed in real time to quickly determine the fault area. Reference [8] proposes a hybrid algorithm based on bats and differential evolution to solve the existing question with distributed power supply positioning effect is not ideal., and this hybrid algorithm also solve the question that the fault information distortion will affect the fault segment positioning accuracy. Reference [9] proposed a distributed intelligent current protection scheme based on the relationship between the distance of the distributed power source from the fault.
point and the short-circuit current. Using the principle of fault secondary positioning, the fault section can be quickly isolated and the power supply in the non-faulty section can be restored. Reference [10] uses the phase angle difference of the fault current to solve the problem of distribution network section located with distributed power supply under the condition of small transition resistance.

In this paper, the instantaneous symmetry component method is applied to the micro-grid, and a fault feature quantity method based on the instantaneous positive sequence current amplitude is proposed. According to the distributed power supply grid-connected standard, the most extreme short-circuit current that the distributed power source can provide is considered. The instantaneous positive sequence current frequency amplitude is extracted by the instantaneous symmetrical component method using the data measured before and after the occurrence of the fault. And the purpose is to distinguish the upstream and downstream fault sections. The research shows that the fault zone positioning method can satisfy the situation that the fault zone positioning method can effectively distinguish between the fault zone and the non-fault zone under the condition that the micro-grid accesses the distribution network.

2. Another section of your paper

The micro-network diagram is shown in Figure 1. When DG is connected to the C bus monitoring points 1 and 2 are set on line AB, monitoring points 3 and 4 are set on line BC, monitoring points 5 and 6 are set on line CD, and monitoring point 7 is set on DE. 8, line AF and so on. The following uses distributed power to access different locations for fault analysis.

![Figure 1. Simplified view of a micro-grid](image)

2.1. Distributed power supply access to the downstream of the fault point

When there is a three-phase short-circuit fault at the upstream F1, the circuit equivalent circuit diagram is shown in Figure 2.

![Figure 2. Equivalent circuit of F1 three-phase fault in micro-grid](image)

In Figure 2, the equivalent impedance (including internal resistance) from bus A to the system power supply is $Z_s$, the length of the fault occurred from the bus A is $\alpha Z_{sl}$, the impedance of line BC is $Z_{bc}$, the impedance of DG is $Z_{DG}$, the impedance of the line CE and the impedance of the load carried by the line CE are a total of $Z_{cd}$, The total equivalent impedance of the feeders lines L2 and L3 and the load they carry is $\frac{Z_{sl} + Z_{cd}}{Z_{sl} + Z_{cd} + Z_{cd}}$, $U_s$ is the normal voltage of this short circuit point before the fault occurs, $I_1, I_2, I_{DG}$ is the current flowing through monitoring point 1, monitoring point 2 and the current provided by DG, respectively.
The short-circuit current $I_1$ flowing through monitoring point 1 is:

$$I_1 = \frac{U_s}{(Z_s + \alpha Z_{AB})/\alpha + Z_{AB}/Z_{AL} + Z_{AL}/Z_{DL}}$$

(1)

The short-circuit current $I_2$ flowing through monitoring point 3 is:

$$I_2 = \frac{S_{DG}}{U_{fualDG}}$$

(2)

When the BC two-phase short circuit fault occurs at the upstream F1, the circuit's positive and negative sequence network equivalent diagram is shown in Figure 3. The distributed power model uses a positive-sequence control strategy, which means that only positive-sequence currents are output when symmetrical and asymmetrical faults occur.

![Figure 3.(A) F1 fault positive sequence network equivalent](image1)

![Figure 3.(B) F1 fault negative sequence network equivalent](image2)

According to the superposition theorem, the magnitude of the positive sequence current $I_{u(1)}$ flowing through the monitoring point 1 under the action of the distributed power supply is:

$$I_{u(1)} = \frac{U_f}{Z_{S1} + Z_{S2}}$$

(3)

The magnitude of positive sequence impedance $Z_{S1}$ in the positive sequence equivalent network is:

$$\left[ \frac{Z_{AB} + Z_{AL}}{Z_{AL} + Z_{DL}} \right] / \left[ (1 - \alpha) Z_{AB} + Z_{BC} + Z_{CE} \right]$$

(4)

and the value of the negative sequence impedance $Z_{S2}$ that in the negative-sequence equivalent network is:

$$\frac{Z_{AB2} + Z_{AL2}}{Z_{AL2} + Z_{DL2}} / (1 - \alpha) Z_{AB2} + Z_{BC2} + Z_{CE2}$$

(5)

The magnitude of positive sequence current $I_{u(1)}$ that flowing through the monitoring point 3 is:

$$I_{u(1)} = \frac{S_{DG}}{U_{fualDG}}$$

(6)

By comparing the magnitudes of the short-circuit currents when different types of phase-to-phase short circuits occur, the conclusion can be reached when the distributed power supply accesses the upstream fault point: that is, when the micro-grid generates a phase-to-phase short circuit fault, the instantaneous positive sequence current at the upstream of the point is significantly different from the instantaneous positive sequence current at the downstream of the fault point and the non-fault branch.
2.2. Distributed power supply access to the upstream of the fault point

When the three-phase short-circuit fault occurs at the end of the distributed power supply downstream of the CD line at F2, at this point, the access point of the DG is upstream of the fault point. The network equivalent circuit diagram of the circuit is shown in Figure 4.

Figure 4. Three-phase fault distribution network equivalent circuit in F2

In Figure 4, the equivalent impedance (including internal resistance) from bus A to the system power supply is $Z_A$, the length of the fault occurred from the bus A is $k_2$, the impedance of line BC is $Z_{BC}$, the impedance of line CD is $Z_{CD}$, the impedance of DG is $Z_{DG}$, the impedance of the line CE and the impedance of the load carried by the line CE are a total of $Z_{CE}$, $U$ is the normal voltage of this short circuit point before the fault occurs, $I_1, I_2, I_{DG}$ is the current flowing through monitoring point 3, monitoring point 5 and the current provided by DG, respectively.

Then the amplitude of short-circuit current $I_1$ that flowing through the monitoring point 4 is:

$$I_1 = \frac{U_s}{Z_A + Z_{AB} + Z_{BC} + Z_{CD}}$$

(7)

After the DG is connected to C through the inverter, the amplitude of short-circuit current $I_2$ that flowing through the monitoring point 5 is:

$$I_2 = \frac{U_s}{Z_A + Z_{AB} + Z_{BC} + Z_{CD}} + I_{faultDG}$$

(8)

When the BC two-phase short-circuit fault occurs at the downstream end of the distributed power source, that is, at the end of the CD line at F2, the positive and negative sequence equivalent circuit of the circuit is shown in Figure 5.

Figure 5.(A) F2 fault positive sequence network equivalent

Figure 5.(B) F2 fault negative sequence network equivalent

Through the comparison of short-circuit currents of different types of phase-to-phase short circuits, it can be concluded that, when a distributed power supply is connected, a phase-to-phase short circuit fault occurs in the distribution network, the amplitude of the instantaneous positive sequence current in the upstream is greater than the amplitude of the instantaneous positive sequence current in the downstream of the fault point and the non-fault branch.
3. Fault Section Determination Method Based on Positive Sequential Current Amplitude

Through the above analysis can be obtained, whether distributed power supply access upstream or downstream of the fault point, after the phase short-circuit fault occurs, the instantaneous positive sequence current is mainly distributed upstream of the fault point (fault point to the bus part), compared to the point of failure The transient positive sequence current of the downstream and the instantaneous positive sequence current amplitude of the non-faulty branch are small. This feature provides strong theoretical support for fault section location. This chapter will analyze the method of locating the faulty section.

3.1. System Failure Additional State Model

Taking the simple power system of Fig. 6 as an example, it is equivalent to Fig. 7(a). As shown in Fig. 7, when the F point in the middle of the MN line is faulty, we can use the additional state of the fault to decompose Fig. 7(a). The basic idea is that after the F point is short-circuited, we can think of the F point as a series of two voltage sources. The two voltage sources are equal in magnitude and opposite in phase. The voltage of the voltage source is the voltage at point F when the system is running normally and set to \( U_F \). From this, we can decompose the fault state diagram (a) in Figure 7 into a superposition of the normal operating state diagram (b) and the fault additional state diagram (c). Take “m” as an example:

\[
U_m = U_{mg} + U_{mg} \quad I_m = I_{mg} + I_{mg} \quad (9)
\]

In the formula: The m-side voltage and current in the fault state are \( U_m \), \( I_m \). The m-side voltage and current in the non-fault state are \( U_{mg} \), \( I_{mg} \). The m-side voltage and current in the additional fault state are \( U_{mg} \), \( I_{mg} \).
After the distributed power supply is connected to the distribution network, there are two power supplies between the connection point and the system power supply. We can equate these two power supplies and the complicated circuit structure between the impedances into a simple structure of a power supply and an impedance. Before and after the conversion, the internal structure of the two circuits has changed, but the external circuit basically has no effect. Therefore, we can study the circuit structure after conversion, and calculate the transient positive sequence current in the fault segment positioning by calculating the equivalent fault additional state of the transformed circuit. At the same time, since the three-phase load is parameter-balanced and its connection method is star connection scheme, it can be obtained:

\[
\Delta U_N = S \Delta U' = \begin{bmatrix} \Delta U_N & \Delta U'_N & \Delta U'_N \end{bmatrix}^T
\]

\[
\Delta i^s_{th} = \Delta i^s_{th} = \Delta i^s_{th} = 0
\]

That is, in a additional fault state network model, the three-phase load is in an open state and the above formula can also eliminate the effect of the load on the fault characteristics.

3.2. Instantaneous symmetry decomposition of fault additional state model

In the case of a phase-to-phase short circuit, the positive sequence abrupt change of the short-circuit current can be obtained by using the additional state of the fault, which can be used as the judgment basis of the fault section. For three-phase short-circuit faults can be directly applied, but for the two-phase short-circuit fault is an asymmetric fault, the need to convert the asymmetry into a symmetrical amount to facilitate the calculation. In order to extract the instantaneous positive sequence current at the time of occurrence of asymmetrical faults, the instantaneous symmetrical component transformation method is selected. Its formula can be described as:

\[
\begin{bmatrix}
i^s_a \\
\frac{1}{3} i^s_{ab} \\
\frac{1}{3} i^s_{ca}
\end{bmatrix} =
\begin{bmatrix}
1 \\
\frac{1}{2}s_{240} \\
\frac{1}{2}s_{240}
\end{bmatrix}
\begin{bmatrix}
i^o_a \\
i^s_{ab} \\
i^s_{ca}
\end{bmatrix}
\]

(12)

For the transient sequence network model with additional states of fault, the network is a time domain sequence network and can describe the dynamic process of phase-to-phase short-circuit faults. Although the instantaneous order network is a complex variable network, in its network model, except that the power source is a complex number, its structure and parameters are the same as the positive and negative sequence networks obtained by the traditional symmetrical component method.

According to the analysis of the difference between the upstream and downstream fault points, the instantaneous positive real-sequence currents at each detection point on the fault line can be obtained. So the expression of the positive sequence current at each detection point upstream of the fault point is:

\[
\Delta i^s_{up} = \Delta i^t_{up} = \Delta i^s_{up} = \Delta i^s_{up}
\]

(13)

The positive sequence current at each monitoring point downstream of the fault point is divided into two cases:

\[
\begin{cases}
\Delta i^s_{down1} = \Delta i^s_{down2} = ... = \Delta i^s_{downn} \\
\Delta i^s_{down1} = \Delta i^s_{down2} > ... > \Delta i^s_{downn}
\end{cases}
\]

(14)

The first case is the instantaneous positive sequence current of the downstream detection points when the distributed power supply accesses the upstream fault point. The second case is the instantaneous positive sequence current of the downstream detection points when the distributed power supply is connected downstream of the fault point. For these two cases, the positive sequence current difference between the fault point upstream and the fault point downstream detection point is:

\[
\begin{cases}
\Delta i^s_{fup} - \Delta i^s_{down1} = ... = \Delta i^s_{fup} - \Delta i^s_{downn} \\
\Delta i^s_{fup} - \Delta i^s_{down1} < ... < \Delta i^s_{fup} - \Delta i^s_{downn}
\end{cases}
\]

(15)

According to formula (13), there is a difference in the amplitude of the instantaneous positive sequence current downstream of the fault point. The specific size of this difference is mainly determined by the distributed power grid capacity. According to Q/GDW1480-2015 Distributed Power
Supply Grid-connected Standard, the maximum DG capacity that can be accessed by 10KV distribution network, consider the case of providing the reverse maximum short-circuit current downstream of the DG access fault point for the fault point. After the system fault additional state model is determined, the instantaneous symmetry component method is used to decompose the three-phase current at the upstream of the fault point, downstream of the fault point and the non-fault branch, and the difference of positive sequence current amplitude can be obtained to determine the fault section.

4. Simulation

4.1. Distribution network parameters

Taking a 10kV distribution network as an example, the rated voltage is 10.5kV, and the microgrid is shown in Figure 1. The system lines are all rated overhead lines. The lengths of AB, BC, CD, DE, AF, FG, and GH are 4Km, 2Km, 3Km, 4Km, 5Km, 3Km, and 5Km, respectively. The positive and negative sequence resistances of the unit length are $R_1 = 0.17\Omega/km$, $R_0 = 0.23\Omega/km$ respectively. The unit length of the positive and negative sequence inductances are $L_1 = 1.21mH/km$, $L_0 = 5.478mH/km$ respectively. The positive and negative sequence capacitances per unit length are $C_1 = 0.00969\mu F/km$, $C_0 = 0.008\mu F/km$, Lines set up a monitoring point every 1.5Km and sequentially numbered.

4.2. The effect of the change of fault location on the fault current at each monitoring point

When a three-phase fault occurs at the end of the AB line F1, the maximum capacity that the DG can access is considered. Table 1 shows the instantaneous positive sequence current amplitude measured at each segment of the line. The detection point 1 is the detection point on the AF, the detection point 2 is the detection point on the AB, the detection point 34 is the detection point on the BC, the detection point 5 is the detection point on the CD, and the detection point 6 is the detection point on the DE.

**Table 1.** The positive sequence current of each detection point F1 fault with change of DG’s capacity

| $S_{DG}/MVA$ | 1 | 2 | 3 | 4 | 5 | 6 |
|-------------|----|----|----|----|----|----|
| 0           | 0.685 | 0.914 | 0.914 | 0.914 | 0.9147 | 0.926 |
| 1.5         | 0.742 | 1.400 | 1.2285 | 71.4 | 0.991 | 1.004 |
| 3           | 0.803 | 1.520 | 2.466 | 1.429 | 1.072 | 1.086 |
| 4.5         | 0.866 | 1.634 | 3.702 | 2.143 | 1.156 | 1.171 |
| 6           | 0.931 | 1.757 | 4.9395 | 4.88 | 1.242 | 1.259 |

As shown in Table 1, when a three-phase short circuit fault occurs at F1 upstream of the DG access point, comparison detection point 2 and detection point 3 , the conclusion can be obtained: with the increase in the DG grid connection capacity, the faulty section under fault status is measured, The difference of the instantaneous positive-sequence current amplitude in the non-fault zone gradually decreases, but there is still a significant difference when the DG access capacity is maximum.

When a BC two-phase fault occurs at the end of the CD line F2, considering the maximum capacity that the DG can access, the amplitude of the instantaneous positive sequence current measured at each line detection point is shown in Table 2.

**Table 2.** The positive sequence current of each detection point F2 fault with change of DG’s capacity

| $S_{DG}/MVA$ | 1 | 2 | 3 | 4 | 5 | 6 |
|-------------|----|----|----|----|----|----|
| 0           | 0.274 | 514.4 | 514.4 | 514.4 | 514.4 | 0.430 |
| 1.5         | 0.299 | 539.6 | 539.6 | 539.6 | 561.67 | 0.468 |
| 3           | 0.326 | 566.7 | 566.7 | 566.7 | 611.7 | 0.509 |
| 4.5         | 0.353 | 595.6 | 595.6 | 595.6 | 663.8 | 0.551 |
| 6           | 0.382 | 626.2 | 626.2 | 626.2 | 717.7 | 0.596 |

As shown in Table 2, when a three-phase short circuit occurs at F2, the downstream point of the DG access point, comparison detection point 5 and detection point 6 the conclusion can be obtained: with
the increase in the DG grid connection capacity, the faulty section under fault status is measured, The difference of the instantaneous positive-sequence current amplitude in the non-fault zone gradually decreases, but there is still a significant difference when the DG access capacity is maximum.

4.3. Verification of a new fault location algorithm
Simulate the fault of the downstream feeder through MATLAB to verify the effectiveness of the fault section positioning method. The wind turbine capacity is 6MW, the three-phase current waveforms and positive sequence components before and after the fault detected at the detection point at the detection point of the three-phase short circuit at the end of the CD line F2 are shown in Figure 8.

![Figure 8. Fault current measured at 5 when three-phase short-circuit occurs at the end of AB line](image)

The detection point 1 is the detection point on the AF, the detection point 2 is the detection point on the AB, the detection point 34 is the detection point on the BC, the detection point 5 is the detection point on the CD, and the detection point 6 is the detection point on the DE. The fault determination results at this time are shown in Table 3:

| Results |
|---------|
| 5-6     |

Table 3. Section location results when F2 fault

Combined with the method described in this paper, the conclusion is available from Table 3, the fault zone is between 5-6, that is, a fault somewhere in the CD segment.

From the simulation data in Table 1-3, the following conclusions are drawn: The method meets the requirements of the *Q/GDW1480-2015 Distributed Power Supply Grid-connected Standard*, and it applies different grid-connected distributed power supplies to the grid, different fault locations and different types of faults. The situation can accurately identify the fault zone.

5. Conclusion
This paper establishes a fault section location method based on the real-sequence real-section ratio method. Using Fourier algorithm, the instantaneous positive-sequence real-time current frequency amplitude of the additional state of the fault branch detection points is extracted. By finding the magnitude of the instantaneous real-sequence current amplitude of the two adjacent detection points on the fault branch, the fault segment positioning in the micro-grid can be realized.

The effectiveness of the method was verified by a simulation model was established with MATLAB. The simulation results show that the variation of the characteristic quantity obtained by the simulation is in good agreement with the theoretical analysis. Through simulation, it can be seen that the current waveforms at the upstream of the fault point is significantly different from the current waveforms at the downstream point of the fault point.
This method can deal with various types of failures that may occur in the micro-grid, in the case of distributed power with different capacities connected to the grid, different fault locations and different types of faults. It has a high fault location speed and fault recognition accuracy, high reliability.

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