Research on Fault Location in Distribution Network Based on Fast Fault Transfer Arc Extinguishing Device

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Abstract: In the distribution network equipped with fast fault transfer arc extinguishing device, after a single-phase grounding fault occurs, the fault phase bus is quickly grounded to realize arc extinguishing. At the same time, the traveling wave signal generated during the grounding process of the fault phase bus can realize fault location. The traveling wave signal is subjected to phase-mode transformation, and the time difference of the zero-mode component mutation detected twice at the exit of the fault line is to be recorded. This time difference is the time which it takes for the zero-mode component to go to and fro once between the bus and the fault point. And then the fault distance can be calculated based on it. The integration of arc extinguishing and fault location is realized. The ATP simulation software is used to realize the fault simulation of distribution network. And the accuracy and feasibility of the proposed fault location method are verified.

1. Introduction

In the medium and low voltage distribution network of 35kV and below, the neutral point of the system is often grounded inefficiently, which has the advantage that it can run with fault for a period of time after a single-phase grounding fault occurs. However, after a single-phase arc grounding fault, the arc burning at the fault point for a long time is easy to cause fire accidents and even more serious system faults.

The traditional arc extinguishing method is to install arc suppression coil at neutral point, but with the continuous expansion of distribution network, the fault current of single-phase grounding also increases. Because the arc suppression coil can not compensate the high frequency component and active component, and its capacity is limited, the application of fast fault transfer arc extinguishing device has gradually increased in the field in recent years. The basic principle is that when a single-phase arc grounding fault occurs on the line, the fault phase bus can be grounded metallically and quickly, and the voltage of the original fault point can be reduced so as to extinguish the arc. Not only the fault phase bus grounding can transfer the fault point to inside the station to realize arc extinguishing, but also the signal generated in the grounding process can be used as the signal source of fault location to realize the integration of arc extinguishing and fault locating.

At present, fault location technology includes two categories, Impedance Method [1-3] and Traveling Wave Method. Impedance method has the advantages of simple operation and less resource
consumption, which has been widely used in power transmission network [4-5], but it is greatly affected by grounding resistance when single-phase fault occurs in distribution network. Traveling Wave Method is the method using the time difference formed by the characteristic wave heads of refracted wave and reflected wave of transient traveling wave to detect fault location[6-7]. In the system equipped with fault quick transfer arc extinguishing device, the traveling wave signal generated during the grounding process of fault phase bus provides a new method for fault location.

2. Wave process during fault phase bus grounding

2.1. Phase-mode transformation

When the power grid is disturbed, the transmission process of transient voltage and current traveling waves can be expressed by the second-order partial differential equation:

\[ \frac{\partial^2 I}{\partial x^2} = CL \frac{\partial^2 I}{\partial t^2} \]  

(1)

Where, \( I \) is the current column vector of three-phase circuit; \( L \) and \( C \) are third-order full-rank matrices, reflecting the inductance and capacitance parameters of coupling between lines of unit length. To simplify the calculation, the full rank matrix should be transformed into diagonal matrix by Karrenbauer transform [8-11]. The conversion process is as follows:

\[ I_m = S^{-1} I \]  

(2)

Where, \( I_m \) is the current vector in modulus; \( S \) is Karrenbauer transformation matrix. The transformation matrix for the three-phase line is as follows:

\[ S = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix} \]  

(3)

Substituting equation (2) into equation (1), the current traveling wave equation can be expressed as:

\[ \frac{\partial^2 I_m}{\partial x^2} = C'L \frac{\partial^2 I_m}{\partial t^2} \]  

(4)

Where, \( C' = S^{-1} CS \) , \( L = S^{-1} LS \)

Therefore, the current transformation matrix of the three-phase line can be expressed as follows:

\[ \begin{bmatrix} I_{m0} \\ I_{m1} \\ I_{m2} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \]  

(5)

Where, \( I_{m1} \) and \( I_{m2} \) are the current aerial mode component, forming a loop through two non-fault phase lines. \( I_{m0} \) is the current zero-mode component, and forms a loop through the earth.

2.2. Traveling wave propagation mechanism when arc extinguishing device acting

The schematic diagram of the arc extinguishing device is shown in Figure 1(a). It is assumed that the A-phase grounding fault occurs in the system. After the fault occurs, the A-phase grounding switch of the arc extinguishing device is quickly closed, and the A-phase bus is grounded metallic. According to the superposition theorem, the circuit after the fault phase bus is grounded can be equivalent to the superposition of the network before the fault phase bus is grounded and the additional network, as shown in Figure 1(b). It can be seen from the figure that the power supply of the additional network generates traveling waves.
From the analysis above, it can be seen that after a single-phase fault occurs, the fault phase is quickly grounded, resulting in a sudden change of current traveling wave signal. When the current traveling wave is transmitted to the fault point, the wave impedance is reflected discontinuously at the fault point. Therefore, from the viewpoint of mode component analysis, it can be seen that the zero-mode component is generated at the moment when the grounding switch is put into operation, and the zero-mode component will suddenly change at the fault point and be reflected back to the bus along the fault line. According to Formula (5), the calculation formula of zero-mode component is as follow:

$$I_{m0} = \frac{1}{3}(I_A + I_B + I_C)$$  \hspace{1cm} (6)

In view of the above, this paper proposes a method of single-phase ground fault location by detecting the arrival time of reflected traveling wave head of zero-mode component. Suppose the distance from point F to the beginning of the line is \(l_f\), \(\Delta t\) is the time taken to detect traveling wave component mutation in the station and then detect the zero mode component mutation. Then the expression of fault distance is:

$$l_f = \frac{\Delta t \times v_0}{2}$$  \hspace{1cm} (7)

Where, \(v_0\) refers to the wave velocity of zero-mode component of traveling wave in the overhead line.

Assuming that the sampling rate of the detection device is \(f\), then the above-mentioned fault location method using zero-mode component can be applied when the fault distance \(l_f > l_{f0}\), but it cannot be applied when the fault distance \(l_f < l_{f0}\). Where, \(l_{f0}\) is the applicable minimum line length, which is obtained by Formula (7):

$$l_{f0} = \frac{v_0}{2f}$$  \hspace{1cm} (8)
2.3. Process of fault locating

According to the above analysis, it can be seen that the traveling wave signal generated by the metallic grounding of the fault phase bus after the single-phase arc grounding fault occurs can be used for fault location, thus realizing the integration of arc extinguishing and fault locating. The detailed process of fault locating is as follows.

First step: The system collects the bus zero-sequence voltage and the zero-sequence current of each line in real time. After a single-phase grounding fault occurs, the fault line is selected within 10-20ms by using the transient signal line selection method [12-13]. Meanwhile, the fault phase is judged according to the effective value of the three-phase power frequency voltage.

Second step: Analyze the harmonic content and phase angle, harmonic distortion rate, interharmonic content and other factors of each zero-sequence signal to judge whether an arc grounding fault [14-15] is happening. If it is judged that there is an arc grounding fault, the arc extinguishing device will act to ground the fault phase bus, and the detection device will record the time difference between two times of detecting the zero mode component of the current traveling wave.

Third step: The distance from the fault point to the bus is calculated by Formula (7). If the arc extinguishing is successful, the insulation of the fault point is to be checked, and if the arc extinguishing fails, the fault section is to be isolated.

3. Simulation verification

Use ATP-EMTP simulation software to establish a single-phase arc grounding fault model in 10kV neutral point ungrounded system. And using TACS controlled resistor, numerical integration element and comprehensive mathematical element of TACS module to realize Mayr Arc Model [16-17]. Collect the arc current and arc voltage by EMTP_OUT pointer, and send them to integrating element and exponential element. Transmit them back to T-controlled resistor after calculating arc impedance. The arc time constant is 7x10^{-4}s, and the dissipation power is 600W. As shown in Figure 2, suppose the length of the third outgoing line is 20km, and an arc grounding fault happens to A-phase at a place 10km away from the bus exit at the time of 0.1s. At the time of 0.195s, the arc extinguishing device acts, the A-phase bus is grounded. The sampling frequency is 1MHz, and the zero-mode wave velocity of the line is 263.46m/us.

Figure. 2 Simulation schematic diagram of 10 kV system
Figure 3 shows the waveform of the zero-mode component detected at the exit of the fault line. The time when the zero-mode component is detected for the first time is 195.002ms, and the reflected wave is detected at 195.078ms. According to Formula (6), the fault distance is 9.994km, the absolute error is 6m, and the relative error is 0.06%.

![Figure 3 Zero-mode component waveform](image)

Change the location of the fault point, and the corresponding measurement results are as shown in Table 1.

| fault location/m | calculation position/m | absolute error/m | relative error/ |
|------------------|------------------------|------------------|----------------|
| 3000             | 2984.83                | 15.17            | 0.50%          |
| 5000             | 4963.78                | 36.22            | 0.72%          |
| 8500             | 8583.68                | 83.68            | 0.98%          |
| 12000            | 12060.42               | 60.42            | 0.50%          |
| 15000            | 14969.96               | 30.04            | 0.20%          |
| 17000            | 16923.45               | 76.55            | 0.45%          |

From the simulation results, it can be seen that the method proposed in this paper has high accuracy and implement ability, and combining it with the arc extinguishing device can realize the integration of arc extinguishing and fault location.

4. Conclusion
In the system equipped with fast fault transfer arc extinguishing device, fault location can be realized by using traveling wave signal generated by grounding of fault phase bus. The time difference between the first detection of zero-mode component mutation and the second detection of zero-mode component mutation is the time which is taken for zero-mode component to go back and forth between bus and fault point once. In addition, the traveling wave signal adopts the current signal, so there is no need to supply an additional voltage to traveling wave signal detection device, thus the feasibility is strong. In practical works, the influence of intermittent arc with strong randomness on traveling wave location results still needs further study.
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