New method for transient line selection in distribution system based on grounding fault transferred

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Abstract: When single-phase arc grounding fault occurs in the neutral ungrounded distribution system, the fault can be transferred by artificially grounding the faulty phase of the busbar, which can effectively improve the fault handling capability of distribution system. The theoretical analysis shows that the characteristic of transient zero-mode current is obviously different between grounding fault and fault transferred. That is to say, in the two grounding processes, the directions of the transient zero-mode current of the fault line are opposite and the direction of the transient zero-mode current of the non-fault line is identical. So, the fault line can be determined based on this theory. The zero-mode current of each line is analysed by wavelet packet decomposition, and the feature band is selected according to the point of maximum energy. The correlation coefficient polarity between two reconstructed data, each is extracted from the first quarter of power cycle of grounding process in respective feature band, is used to determine the criterion for fault line selection. This method only uses its own line information to choose fault line without any other line information. Simultaneously, number of simulation results shows that the method is accurate and reliable.

1 Introduction

The middle- to low-voltage distribution networks mostly adapt neutral point not-valid grounding (so called ‘small current grounding system’). When single-phase grounding fault occurs in this system, system can continue to run for 1–2 h in result of low grounding current. If the fault remains unsolved, lower grounding phase voltage and higher non-grounding phase voltage can cause serious threat to insulation of electrical equipment. Those threats can cause fault diffusion and electric shock accident. Therefore, accurately identifying the fault line is important for safe and stable operation of power distribution.

When single-phase arc grounding fault occurs, over-voltage which is 3.5 times of peak value of normal voltage would be caused. Strong over-voltage for a long term is bound to destroy system insulation and cut-off power supply to users. The existing fault line selection technology is not ideal and effective. Low steady-state current amplitude and intermittent arc grounding are main difficulties for fault line selection [1]. Due to unstable arc at fault point, there is no stable steady-state information. So, the fault line selection method based on fault steady-state component is not reliable [2]. Other fault line selection method which is based on fault transient components can overcome the shortages of steady-state component line selection method and has become the research focus [3–6], but most of these methods need to use transient information from both fault line and non-fault line. That line selection accuracy is significantly reduced when only two lines are in system.

Grounding fault transferred is a new arc grounding fault handling method. After single-phase arc grounding occurred, rapidly close grounding switches of fault phase of bus line can effectively suppress the arc over-voltage and eliminate this fault. Its unique two grounding processes present different characteristics, and this difference in characters provides a new idea for arc fault line selection. Simultaneously, this method only needs fault line information to realise fault line selection.

Above all, this paper provides a new method for transient-state line selection in distribution system based on grounding fault transferred. Proposed approach is based on wavelet decomposition and single-branch reconstruction. This method extracts transient zero-mode current from characteristic frequency band and uses the correlation coefficient of transient zero-mode current of two grounding processes as polar fault line selection criteria. The feasibility and correctness of this method have been verified by large amount of simulation experiments in Power Systems Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC).

2 Fault analysis

This part analyses the fault characteristics of single-phase grounding fault and single-phase grounding fault based on grounding fault transferred.

2.1 Single-phase grounding fault

When single-phase arc grounding fault occurs in the neutral ungrounded distribution system, the zero-mode network of the system is constructed by ground capacitances of lines and an equivalent zero-mode power source which has been added at fault point. The distribution of zero-mode current can be seen from Fig. 1. Zero-mode current, from fault point to bus line, flows to earth through ground capacitance of system and every non-fault line. Other zero-mode current, from fault point to end of the line, flows towards earth through ground capacitance on this line. Due to large number of feeders and short length of each feeder in distribution system, the zero-mode current from fault point to bus is larger than and opposite to zero-mode current in part from fault point to end of the line.

Let \( U_f \) represents zero-mode voltage, \( I_f \) represents ground fault current, \( I_N \) represents zero-mode current of fault line \( L_f \), \( I_n \) represents zero-mode current of non-fault line \( L_n \), and \( I_u \) represents system zero-mode current. Zero-mode current flowing through the exit of any non-fault line is equal to the current of ground capacitance on this line, the direction of which is from bus to line. The zero-mode current flows through the exit of fault line equal to...
the sum of zero-mode currents of every non-fault line and system, the direction of which is from line to bus. That is shown as follows:

\[ I_{0i} = 3j\omega C_0 I_{00} \]  

(1)

\[ I_{N'} = I_{00} + \sum I_{0i} = 3j\omega (C_0 \Sigma - C_0 N) I_{00} \]  

(2)

This shows that the zero-mode current at the exit of fault line is larger than any non-fault head zero-mode current and towards opposite.

2.2 Grounding fault transferred

Grounding fault transferred is an effective way to eliminate arc fault. Fast switches are installed on all three-phase lines of bus. When system is operating normally, switches stay on open. When single-phase grounding occurs on line, switch on fault line is closed and connected to ground, and after that, immediately transferred unstable grounding at fault point to stable metal grounding. Therefore, arc fault can be extinguished effectively [7–9]. At this time, distribution of system zero-mode current is shown in Fig. 2. Any zero-mode current flow through the exit of line is the grounding capacitance current. The direction of this current is towards line from bus.

In summary, in the single-phase grounding fault and grounding fault transferred fault cases, the fault line zero-mode current flows in the opposite direction and non-fault line zero-mode current flows in the same direction.

3 Fault line selection

3.1 Line selection principles and approaches

According to theoretical analysis from last part of paper, after single-phase arc grounding occurred, rapidly closing grounding switches of fault phase of bus line can cause obviously changes of characteristics of fault line. However, this movement causes tiny influences on non-fault line. As this paper mentioned, in the two grounding processes, the directions of zero-mode current on fault lines are opposite and the directions of zero-mode current on the non-fault line are the same. So, this direction criterion can be used as approach to distinguish fault line.

Wavelet packet has a good frequency domain division characteristic. This paper implements db wavelet to decompose zero-mode current from feeder at each measuring point according to certain frequency band. Following (3) to, respectively, determine the frequency band with maximum energy of two grounding processes, this is the most concentrating band of current of ground capacitance. This band is also the most obviously frequency band of fault characteristic. In characteristic frequency band, reconstruct two zero-mode currents of two grounding processes, and transient zero-mode current is extracted from characteristic frequency band.

\[ e = \sum [\omega(n)]^2 \]  

(3)

In this equation, \( j \) represents the number of wavelet decomposition layers, \( k \) represents the \( k \)th point wavelet decomposition, and \( \omega_k(n) \) is the \((j,k)\) sub-frequency parameters of wavelet decomposition.

Define transient zero-mode current of fault grounding process as \( i_{01} \) and transient zero-mode current of fault transferred process as \( i_{02} \), and the correlation coefficient of two grounding processes of transient zero-mode current is \( r \). That is:

\[ r(\hat{i}_{01}, \hat{i}_{02}) = \frac{\sum_{n=1}^{N} \hat{i}_{01}(n)\hat{i}_{02}(n)}{\sqrt{\sum_{n=1}^{N} \hat{i}_{01}^2(n)\sum_{n=1}^{N} \hat{i}_{02}^2(n)}} \]  

(4)

In this equation, \( n \) is the sequence array of sample. Sampling starts at \( n = 1 \) when the fault occurs. \( N \) is the length of sampled zero-mode current data. Quarter of cycle (5 ms) is chosen as the sample length. This length of sample can fit demand of sampling theorem and ensure enough values for computing [10].

3.2 Fault criteria and process

According to analysis above, this paper proposes a new criterion for distribution transient line selection based on grounding fault transferred. This new criterion can be described as follows: if the correlation coefficient of two grounding processes of transient...
zero-mode current on band is negative, this line can be verified as fault line.

Detailed process of line selection is shown in Fig. 3.

4 Simulation

4.1 System and arc simulation model

This paper builds neutral point ungrounded power distribution simulation model in PSCAD/EMTDC. As shown in Fig. 1, G is unlimited power source, T represents main transformer, transformation ratio of which is 110/10.5 kV and wiring in YNd11. Ti (i represents ith line) represents distribution transformer which is wired in way of Dyn11 and transformed at ratio of 10/0.4 kV. L1, L2, L3, and L4 represent four lines of feeders. The load uses three-phase balanced constant impedance model. Unified equivalents to $P=0.405 \text{ MW}$ and $Q=0.2475 \text{ MVar}$, and power factor is 0.85 in this model. The capacity of capacitive reactive power compensation device is set to 30% of capacity of main transformer, which is 173 $\mu$F of each capacitance on each phase.

Electrical arc has complex characteristics and is influenced by many factors. The arc dynamic model builds on balanced energy theory of arc gap. This theory is based on balanced energy theorem, which proposes to regard electrical arc as a cylindrical gas passage. Arc presents highly non-linear changing characteristics. Arc can be regarded as a variable resistance for arc conductivity changing with arc energy. Although there is comprehensive study of various papers, this paper presents an easy-build and relatively accurate arc model [11–14]. Assume at time equal to 0.12 s (the time when value of C-phase voltage is maximum), arc grounding fault occurs on line L2 and arc burning is stable. Waveform of voltage and current of arc are shown in Figs. 4 and 5.

4.2 Simulation analysis and conclusion

For distribution network of Fig. 7, when time is at 0.12 s, the C phase of L4 which is 3 km away from bus occurs at intermittent arc grounding fault. At 0.135 s, fast switch of fault phase on bus closes entirely. Waveform of voltage and current at fault point is shown in Fig. 8.

As we can see from Fig. 8, after grounding fault be transferred, current at fault point decreased rapidly. Then, most of fault current flows into the ground through the grounding phase of bus. Voltage at fault point closes to zero. Non-fault phase voltage stays on line voltage. Arcing voltage is limited under recovery strength of arc medium. So, arc can be effectively extinguished. Therefore, the first section of theoretical analysis is established. See Figs. 9 and 10.

Take 10 kHz sample frequency as example, and follow process which is described in Section 2.2 for fault line selection. Due to space limitation, this paper only provides the zero-mode current time-domain waveform of fault line L2 and non-fault line L1. Waveform of zero-mode current characters presents visible differences between fault line and non-fault line in two times of grounding processes.

Collect data from fault line L2 and non-fault line L1 5 ms after single-phase grounding and grounding fault transferred and analyse...
the data by four-layer wavelet decomposition. The waveform of transient zero-mode current of the exit of fault line in frequency band is shown in Fig. 11. The waveform of transient zero-mode current of the exit of non-fault line in frequency band is shown in Fig. 12.

Use (4) to compute the correlated coefficient of transient zero-mode current of two grounding processes in respective feature band, and the result is shown in Table 1.

At present, the method of line selection based on the similarity weakest principle of capacitance current between the fault line and faultless line in the characteristic band mainly uses the amplitude and polarity of transient capacitance current correlation coefficient of fault line and faultless line in the characteristic band to construct criterion. This criterion is invalid when there are only two lines in distribution system. To build this situation, delete line L1 and line L3 from distribution system as shown in Fig. 7. Use proposed fault line selection method of this paper to select fault line, and the result is shown in Table 2.

Concluded from Table 2, the distribution transient line selection method based on grounding fault transferred can be used to detect fault line when there are only two feeder lines.

Meanwhile, large amount of experiments has been done to verify the feasibility and correctness on variable fault locations. The results are shown in Table 3.

5 Conclusion

This paper analyses the characteristics of transient zero-mode currents of two grounding processes, single-phase grounding fault, and grounding fault transferred, and then provides a new method for transient line selection in distribution system based on grounding fault transferred.

Compared to traditional line selection method, this method effectively uses the transient information. It only uses the
information of fault line to determine whether a fault has occurred without using zero-mode current data from other lines, which is easier than other methods. Meanwhile, this study uses number of simulations to prove that this method has strong adaptability and high reliability.

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7 References

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Table 1 Results of fault line selection

|     | L1   | L2    | L3   | L4   | Results |
|-----|------|-------|------|------|---------|
| f1  | 0.041| −0.044| 0.041| 0.038| L2      |

Set fault f1: L2 is 6 km from bus, the C phase of which occurs at grounding fault. Set fault f2: line L1 is 12 km from bus, the C phase of which occurs at grounding fault. Set fault f3: line L1 is 4 km from bus, the C phase of which occurs at grounding fault.