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Fault Section Location Based on Adaptive Correlation Analysis in the Neutral Non-Effectual Grounded System

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ABSTRACT

A novel fault location method to identify the single-phase earth fault occurred in the neutral non-effectual grounded system is presented. It is a practical improvement which presents the method for determining the adaptive correlation coefficient threshold. This study focuses on the synchronization of signal processing, the improvement of the correlation coefficient and the threshold; widen the criterion gap between the fault section and the healthy fault section. Large amounts of ATP simulations show that the fault location algorithm based on adaptive correlation analysis can accurately determine fault points when applied to the neutral non-effectual grounded system.

Key words: Single-phase earth fault, correlation analysis, self-adaption, simulation research

INTRODUCTION

Most of medium-voltage distribution network lines in China are overhead lines and more than 80% of faults originate from the single-phase short circuit fault (Hanninen and Lehtonen, 1998). When single-phase earth fault occurred in small current grounding system, line voltage remains symmetrical and does not affect the normal use of electricity users. However, the non-fault phase-to-ground voltage would be increased to the $\sqrt{3}$ times the original. Under the special condition, the grounding capacitive current might cause the fault point across, produce instantaneous over voltage, lead to the insulation breakdown and it is likely to be expanded to 2-phase or 3-phase short circuit which could greatly decrease the safety and reliability of distribution network.

Years of research by many experts at home and abroad, the location method based on the differences among used signal is mainly divided into the active method and passive method. Passive method, as the primary research method, includes impedance method (Mora-Florez *et al*., 2008), traveling wave method (Tao, 2012) and the steady zero-sequence reactive power direction method (Zhang *et al*., 2008). But each method has limitations in practical application: Impedance method is likely to be influenced by many factors such as circuit and system operation mode and has a relatively simple application; traveling wave method is not suitable for distribution lines which are of complicated structure and many branches; the steady zero-sequence reactive power direction method is not applicable to neutral grounded though arc suppression coil. In recent years, some scholars have tried to adopt mathematical analysis tool to fault location in small current grounding system, such as the wavelet transform (Pang *et al.*, 2007) and mathematical morphology (Ren *et al.*, 2008). Because of the weakness fault current, unstable arc when the ground fault occurs and the limitations of the methods used, the lack of theoretical basis, the small current grounding fault location has not been effectively resolved.

In this study, by means of calculating the maximum value of the correlation coefficient, improving the correlation coefficient and threshold based on the correlation analysis theory, this method has eliminated the calculation error due to asynchronous data acquisition from feeder terminal unit and easily solved the key technology problem of the field application. A large number of ATP simulations demonstrate that, this adaptive correlation analysis method has raised the accuracy of the fault location and meet the practical requirements to a great extent which is immune to various neutral point operation modes, different fault inception angles and different grounding resistance.

MATERIALS AND METHODS

The previously published studies on the correlation coefficient may not be suitable for fault location because of its disadvantages of the algorithm. The characteristics of transient zero-mode power was briefly introduced here when single-phase earth fault occurred in small current grounding system. Then the adaptive location algorithm is proposed based on the correlation coefficient.

Description of the characteristics of transient zero-mode power: Since the three-phase system is influenced by the electromagnetic coupling between phases, mutual inductance and distributed capacitance, it is necessary to adopt Karrenbaur transform (Yan *et al.*, 2014) to three-phase system which can be changed as a non-coupling modular field for the suppose of calculating the zero mode power. When the neutral non-effectual grounded system is in fault, the system will generate transient zero-mode signal and produce a virtual voltage source in the fault point (Wang *et al.*, 2012), as shown in Fig. 1. Tian *et al.* (2010), stated that owing to the influence from the voltage source to the fault line, the transient zero-mode power signal from fault point to the bus bar terminal flows from N to M which has a low resonant frequency and a large signal amplitude and it is equal to the sum of other healthy lines' transient zero-mode power; the transient zero-mode power signal from the fault point to the load terminal flows from P to Q which has a high resonant frequency and a small signal amplitude. From Fig. 2, when single-phase ground fault occurs in the NP section, the two ipsilateral adjacent detecting points have small power amplitude

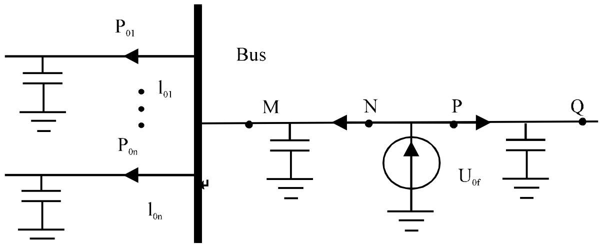

Fig. 1: Equivalent circuit of zero-mode network

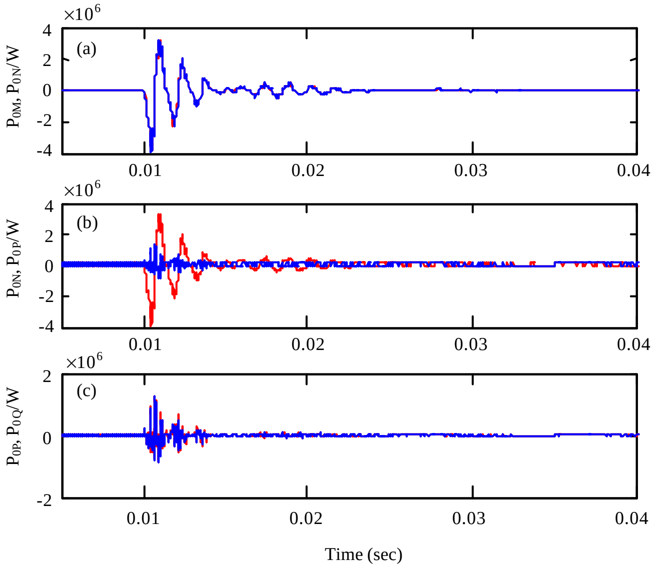

Fig. 2(a-c): Zero-mode powers (a) M and N, (b) N and P and (c) P and Q in healthy section and faulty section, waveform

differences, consistent initial polarity and high waveform similarity, while the differences of the amplitude between the two detection points on both sides of the fault point is large and the initial polarity is opposite with a low waveform similarity.

Method of location algorithm based on correlation coefficient of transient zero-mode power

Initial scheme of fault location: The correlation analysis theory is selected to reflect the characteristics of the transient zero-mode power (Tian *et al*., 2011). Zero-mode power of every two adjacent detection points in the fault line is expected to be used as a sample signal to calculate the correlation coefficient; therefore, the correlation coefficient equation is as follows:

$$\rho = \frac{\sum_{n=0}^{N-1} p_{01}(n)p_{02}(n)}{\sqrt{\sum_{n=0}^{N-1} p_{01}^2(n)\sum_{n=0}^{N-1} p_{02}^2(n)}} \tag{1}$$

where, p_{01} (n) and p_{02} (n) are, respectively transient zero-mode power of the adjacent two detection points; n is the sampling sequence and n = 0 indicates that the fault occurs; N-1 is the length of data window of power. In general, threshold value of the correlation coefficient σ is 0.7 or 0.8. If $|\rho|<\sigma$, it is decided as the fault section; if $|\rho|<\sigma$, it is decided as the healthy section (Tian *et al*., 2011).

The initial scheme of locating algorithm based on the correlation coefficient of transient zero-mode power has the following disadvantages by Eq. 1.

The extracted power signal must be synchronized but there exists time error between each measuring device.

The imperfect correlation coefficient criterion might not determine fault point accurately, without taking consideration of the situation when correlation coefficient is negative, i.e., when ρ is negative and $|\rho|<\sigma$, as the ground fault occurs, it is prone to misjudgment.

Ignoring the certain distribution system where the downstream line of fault point is long and the situation that the difference of amplitude and resonant frequency of transient zero-mode power on both sides of fault point is small. Hence, it is needed to improve the correlation coefficient equation and the improving measures are as follows.

Synchronous signal processing: In order to avoid time error caused by the two detection points, it is necessary to adopt bidirectional waveform translation method to obtain the maximum correlation coefficient; correspondingly, the computational equation of the maximum correlation coefficient is as follows:

$$\rho_{\max} = \max \frac{\sum_{n=0}^{N-1} p_{01}(n) p_{02}(n+n_0)}{\sqrt{\sum_{n=0}^{N-1} p_{01}^2(n) \sum_{n=0}^{N-1} p_{02}^2(n+n_0)}} \tag{2}$$

where, n_0 is the translation point number of the largest correlation coefficient; f is the sampling frequency of signal; Δt is time error caused by the master station of distribution network, $n_0 \in [-f.\Delta t, -f.\Delta t+1, ..., 0, 1, ..., f.\Delta t]$. By means of bidirectional movement, calculating the maximum value of the correlation coefficient can effectively solve the asynchronous signal problem caused by the inconsistent initial time of the signal acquisition of transient zero-mode power. With regard to the two signals that have different starting time and similar waveforms, one characteristic signal should be regarded as the reference signal and the other should be translated point by point. Calculating correlation coefficient for different translation points and the larger the correlation coefficient value is, the better overlap of two waveforms have, with the smaller difference of initial time. The two signals can be regarded as synchronization when value of the correlation coefficient is the largest. As for the similarity of the two signals is very low, by means of bidirectional movement, the maximum correlation coefficient is almost close to zero which meets the principle of relative positioning as usual.

Correction of correlation coefficient and threshold: A reliable and effective correlation coefficient fault criterion should widen the gap between the fault section and the healthy fault section, reduce the correlation coefficient effectively. In order to reflect similarity of zero-mode power waveform more precisely, the amplitude of zero-mode power can be taken into consideration. With the introduction of the amplitude, the correlation coefficient calculation result is prone to be greatly improved and the improved equation is as follows:

$$\sigma = \rho_{\max} - (1-|\rho_{\max}|) \frac{\min\left(\sum_{n=0}^{N-1} p_{01}^2, \sum_{n=0}^{N-1} p_{02}^2\right)}{\max\left(\sum_{n=0}^{N-1} p_{01}^2, \sum_{n=0}^{N-1} p_{02}^2\right)} \tag{3}$$

In this equation, amplitude difference of zero-mode power measurement is very small for the two ipsilateral adjacent detecting points (generally, $\rho_{max}>0.9$); therefore, measurement about the sum of the amplitude has tiny differences within the time sequence of samples. While the amplitude difference of zero-mode power measurement varies widely for the two adjacent detection points on both sides (generally, $-1\leq\rho_{max}\leq 0.2$), therefore, measurement about the sum of the amplitude has big differences within the time sequence of samples. Even in the distribution system whose downstream of the fault point has a long line and in the special situation of high waveform similarity of the two sides of the detecting point, it's verified by experience that the introduction of zero-mode power amplitude can still effectively decrease the correlation coefficient of the adjacent two detection points.

The threshold can be adaptively set according to the correlation coefficient of each section in the fault lines and the equation is as follows:

$$\sigma_{th} = \sum \sigma_{ij} \Big/ N \tag{4}$$

where, σ_{ij} is the correlation coefficient of each section, N is the total number of fault line sections. If $\sigma_{ij}\geq\sigma_T$, it is decided as the healthy section; otherwise, it is decided as the fault section. The value of the correlation coefficient threshold σ_T is based on σ_{th}, the rules are as follows:

- If $\sigma_{th}<0.2$, then $\sigma_T = 0.2$
- If $0.2\leq\sigma_{th}\leq 0.6$, then $\sigma_T = \sigma_{th}$
- If $\sigma_{th}>0.6$, then $\sigma_T = 0.6$

RESULTS AND DISCUSSION

Experiment results and analysis: The small current grounding system model simulation, analysis and comparison location algorithm was proposed above.

Small current grounding system model: Utilizing the model built by ATP with small current to ground system to verify the validity of the method in this study and it was shown in Fig. 3. The line is composed of six lines L_1~L_6 and the length of them are 20, 15, 24, 8, 16 and 30 km, respectively. The fault occurs on the 10 km position of the line 1, four detection devices of A, B, C and D are installed at the 8.5, 9.5, 10.5 and 11.5 km, respectively. Distributed parameter model was adopted to simulate the practical lines (Zhang *et al.*, 2007) and the positive sequence impedance is: $z_1 = 0.17+j0.38\ \Omega\ km^{-1}$; positive-sequence conductance to ground is: $b_1 = 3.045\ \mu s\ km^{-1}$; zero-sequence impedance is $z_1 = 0.23+j1.72\ \Omega\ km^{-1}$; zero-sequence conductance to ground is $b_1 = 1.884\ \mu s\ km^{-1}$. Line equivalent load impedance of No. 1 and No. 3 is $Z_L = 400+j120\ \Omega$. The transformer is in the shape of Y/Y_0 connection and rated capacity of the transformer is 40 MVA; primary voltage is 220 kV; secondary voltage is 35 kV; no-load losses 35.63 kV; inductance is 0.183 Ω; steady-state magnetizing current is 0.672 A; main magnetic flux is 202.2 wb; magnetizing impedance is 400 kΩ; a winding leakage impedance is 0.4 Ω; secondary winding leakage impedance is 0.006 Ω. As more than 80% fault originate from the single-phase short circuit fault, it is necessary to take the simulation of A-phase to ground fault for an example. According to the model built by ATP, the capacitive current is larger than 20 A and the arc suppression coil should be added to this system.

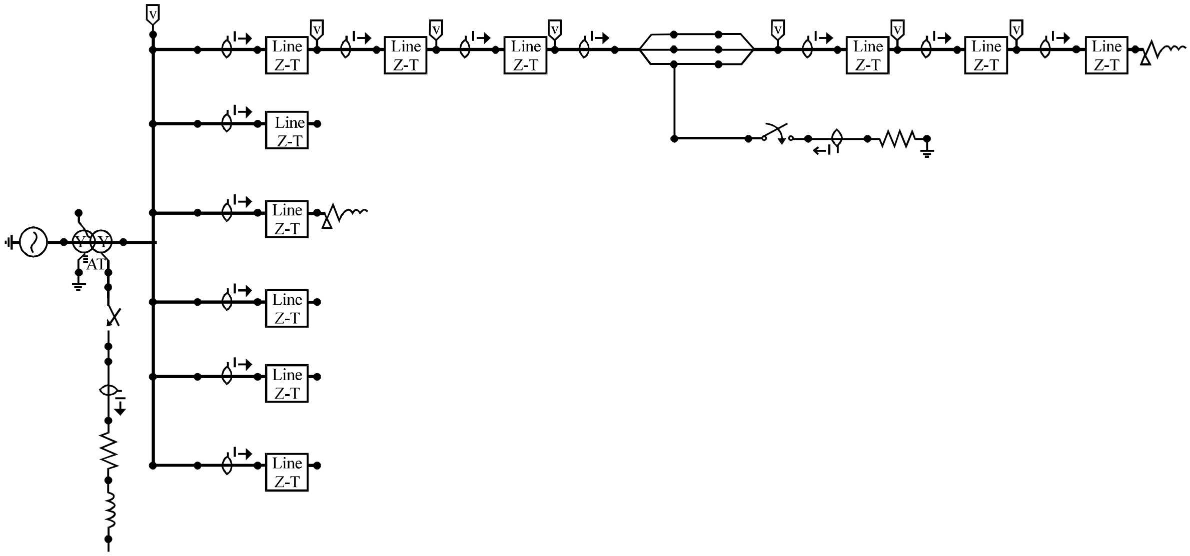

Fig. 3: Model of small current grounding system

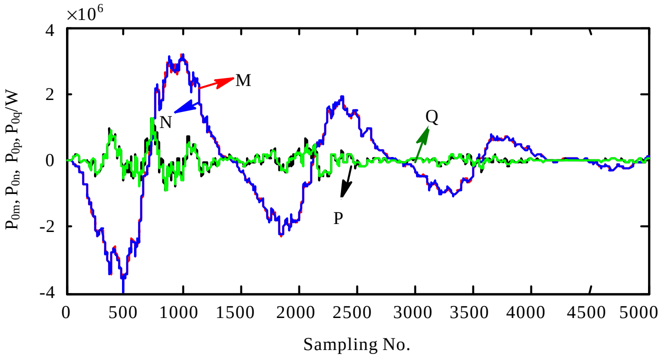

Fig. 4: Waveform of transient zero mode power of data window selected

The sampling frequency is 10^6 Hz and the data window length of one-forth of power frequency cycle (5 msec) is selected to simulate. The basic condition of the simulation are as follows: Inception phase-angle is 0° and the grounding fault occurs in the NP section; grounding resistance is 5 Ω; the detuning is 8%; the simulation step is set as 1 μsec; the single-phase short circuit time is 0.01 sec; the time of termination is 0.1 sec. The waveform of transient zero mode power in 5 msec is shown in Fig. 4.

The data acquired by the simulation is processed by MATLAB and then calculates that the original correlation coefficients $\rho_{mn} = 0.9990$, $\rho_{np} = -0.1083$, $\rho_{pq} = 0.9425$, the amended correlation coefficients $\sigma_{mn} = 0.9980$, $\sigma_{np} = 0.1379$, $\sigma_{pq} = 0.8951$ and the threshold $\sigma_T = 0.5851$. Therefore, it's determined that the fault section is in the NP section and the positioning result is correct.

Now on the condition of given different transition resistance and the initial phase angles of voltage are 0°, 30°, 60° and 90°, calculating the correlation coefficients before and after the correction and the results are shown in Table 1.

Table 1: Correlation coefficient of power under 0°, 30°, 60° and 90°

Resistance/Ω	ρ_{mn}	ρ_{np}	ρ_{pq}	σ_{mn}	σ_{np}	σ_{pq}	σ_r	Results before and after
0°								
5	0.9990	-0.1083	0.9325	0.9980	-0.1379	0.8951	0.5851	NP/NP
20	0.9985	-0.0596	0.9301	0.9976	-0.1093	0.8254	0.5712	NP/NP
100	0.9972	0.0965	0.9286	0.9958	-0.0092	0.8250	0.6000	NP/NP
500	0.9969	0.1834	0.9427	0.9924	0.0135	0.8986	0.6000	NP/NP
2000	0.9984	0.4458	0.9466	0.9868	0.2291	0.8984	0.6000	NP/NP
5000	0.9987	0.5259	0.9465	0.9863	0.3764	0.8995	0.6000	NP/NP
30°								
5	0.9984	-0.3085	0.9771	0.9976	-0.6532	0.9085	0.4176	NP/NP
20	0.9976	-0.1688	0.9724	0.9964	-0.4945	0.9001	0.4673	NP/NP
100	0.9663	0.2515	0.9573	0.9903	-0.1964	0.8903	0.5613	NP/NP
500	0.8905	0.3040	0.9497	0.9937	0.0132	0.9054	0.6000	NP/NP
2000	0.9228	0.6948	0.9846	0.8923	0.4556	0.9789	0.6000	NP/NP
5000	0.9261	0.7250	0.9862	0.8982	0.5069	0.9745	0.6000	Misjudge /NP
60°								
5	0.9964	-0.7482	0.9650	0.9952	-0.8931	0.9327	0.3449	Misjudge /NP
20	0.9942	-0.5514	0.9602	0.9958	-0.7575	0.9459	0.3947	NP/NP
100	0.9905	-0.0935	0.9598	0.9532	-0.3479	0.9402	0.5157	NP/NP
500	0.9886	0.2557	0.9454	0.9846	-0.2026	0.9331	0.5717	NP/NP
2000	0.9909	0.7924	0.9785	0.9845	0.4627	0.9660	0.6000	Misjudge /NP
5000	0.9927	0.8085	0.9782	0.9854	0.5056	0.9667	0.6000	Misjudge /NP
90°								
5	0.9965	-0.8098	0.9606	0.9874	-0.9287	0.9509	0.3396	Misjudge /NP
20	0.9924	-0.7596	0.9588	0.9958	-0.8945	0.9522	0.3512	Misjudge /NP
100	0.9902	-0.5865	0.9565	0.9803	-0.7896	0.9445	0.3784	NP
500	0.9751	-0.4454	0.9624	0.9542	-0.6385	0.9806	0.4528	NP
2000	0.9903	-0.3957	0.9957	0.9255	-0.5482	0.9810	0.4528	NP
5000	0.9917	-0.2085	0.9883	0.9037	-0.3954	0.9801	0.4961	NP

Analysis of algorithm results compared to previously published studies: According to Tian *et al.* (2011), the correlation analysis theory taking advantage of the transient zero-mode power is selected to locate the fault section, however, there are some errors applied to various neutral point operation modes. The reasons are as follows.

In Table 1, the correlation coefficient of transient zero-mode power such as ρ_{mn} and ρ_{pq} is positive and all larger than 0.9, while the correlation coefficient of transient zero-mode power between the two adjacent detection points on both sides such as ρ_{np} is negative, or positive in some cases. If the criterion threshold is taken as 0.7, under the initial phase angle of 30°, $|\rho_{mn}|$ and $|\rho_{pq}|$ are both greater than 0.7, besides, $|\rho_{np}|$ is less than 0.7, so the fault section can be determined accurately. However, the correlation coefficient of the fault section (NP) under 30°, 60°, 90° is positive or negative but $|\rho_{np}|$ is larger than 0.7 sometimes, at this time, the fault section can be misjudged. When the transition resistance is 200 Ω in Table 1, the value of ρ_{np} varies from 0.7924-0.4627 which makes significant differences between the two adjacent detection points on both sides, further widens the gap between the fault section and the healthy fault section. Meanwhile, the threshold is adaptively set as 0.6000 according to each section of faulty line No. 1. ρ_{np} before correction is 0.7924 when σ_T is taken as 0.7, so the previous studies published above can not effectively determine the fault section.

Based on the above analysis, it's possible to misjudge the fault section by the previous studies published above in various neutral grounding systems from the data of Table 1. After the synchronization of signal processing, the improvement of the correlation coefficient and the threshold, this method can improve the accuracy of fault section location for not only different inception phase angles but also various transition resistances.

CONCLUSION

In this study, a novel fault location method of small current grounding is proposed on the basis of adaptive correlation analysis and the method has modified the original correlation coefficient and threshold of the transient zero-mode power signals on both sides of the detection point. A large number of simulation experiments show that the method could be applied extensively, hardly be affected by the structure of the system and the neutral point grounding mode and can effectively adjust the fault criterion by using DA system which greatly improves the correct rate of location and lays a good foundation for the research and practical application of fault location in small current grounding system.

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