Single-Phase-to-Ground Fault Location Method Based on SOGI

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Abstract. Most fault location methods depend on the exact extraction of fault transient feature. However, due to the weak grounding current, arc grounding and intermittent problems, it is difficult to extract the fault transient feature. Based on second-order generalized integrator (SOGI), a single-phase-to-ground fault section location method for neutral point ungrounded system is proposed to address this problem in this paper, which avoids the extraction of fault transient feature. Firstly, the fundamental wave phases of zero sequence voltage and zero sequence current are extracted by second-order generalized integrator. Then, the fault position is located based on their phase difference. Finally, the proposed strategy is tested by the simulation data and the field data. The test results show that the method proposed in this paper can accurately locate fault position. Moreover, the phase extraction method based on SOGI is more accurate than traditional Euler method.

1. Introduction

Most of China's distribution networks adopt the operation mode of neutral point non-effective grounding, in which the neutral point is mainly non-ground [1]. This operation mode can improve the power supply reliability of the system, however, when the fault of single-phase-to-ground occurs, the non-fault phase voltage will rise, and the intermittent arc grounding can easily lead to the overvoltage of the electric arc, which leads to the breakdown of the line insulation and the fault turning into the two-phase fault. Therefore, the fault should be located as soon as possible and eliminated to ensure the safe and stable operation of the power system.

In recent years, researchers at home and abroad have done a lot of research in the field of single-phase-to-ground fault in non-solid earthed network. A fault phase location identification for adjustable speed drives in high resistance grounding system is proposed in [3]. The method can locate the fault phase, which makes the fault location more accurate. However, the method requires high detection accuracy of voltage and current. The fault segment location method based on the phase voltage and current fault components is proposed in [4]. The method is based on the principle that when a single phase grounding fault occurs, there will be positive correlation coefficients between current and voltage fault component derivative of each phase of healthy lines, healthy phases of fault line and fault phase of downstream segments of the fault point respectively. On contrary, the correlation coefficients of upstream segments of fault point are negative. The method overcomes the shortcoming of the large amount of information and the difficulty to obtain the zero sequence voltage and current. However, the method has many parameters to be set. A single-phase-to-ground fault location in multi-brunch distribution network based on unilateral information is proposed in [5]. The location error of the method is less than 0.01km. However, the method changes the single-phase-to-ground fault into the double-phase-to-ground fault by setting the artificial grounding point at the end of the line in the sound phase, which may increase the harm of the fault and endanger the safety of power grid. A new combined method for locating the single-phase fault to earth in PD networks is proposed in [6]. The method firstly uses the impedance-based fault-location algorithm to find the possible fault locations. Then the new method is proposed for determining the fault section using voltage sag matching algorithm. However, the voltage data is not obtained in some cases. In addition, the angle of voltage is difficult to extract because of the complex grid.

Aiming at the current fault location and phase extraction problems, a new phase extraction method of zero sequence voltage and zero sequence current based on SOGI is proposed in this paper. Then the fault is located based on the principle of phase difference location. Finally, the method is verified by simulation data and actual data. The test results show that the method proposed in this paper can accurately locate fault segments and the locked phase of the proposed method is more accurate than that of the traditional Euler method. The phase calculation formula based on SOGI is first derived and applied to small current ground fault location. The fundamental wave phases of zero sequence voltage and current are extracted based on its orthogonal characteristic.

In this paper, a new single-phase-to-ground fault segment location method based on SOGI is proposed. In section 1, the disadvantages of traditional fault location methods are introduced and the new fault location method is proposed. The theory of new fault location method is introduced in section 2. In section 3, the results of laboratory test and field test of this method are shown and compared with traditional phase extraction method. Conclusions are given in section 4.

2. Fault Location Method Based on SOGI

2.1. The Fundamental Phase Extraction Principle Based on SOGI

The generalized integrator can realize the integral action of alternating current signal, and is applied to the proportional-resonant controllers [7], adaptive filter [8]. As an adaptive filter, based on the generalized integrator (GI) structure, the structure of this filter is shown in Fig.1 [9].

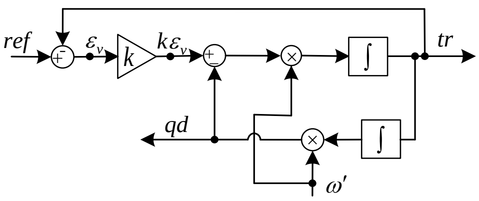

Figure 1. SOGI diagram

The transfer function of the SOGI is given by

$$SOGI(s) = \frac{tr}{k\varepsilon}(s) = \frac{\omega' s}{s^2 + \omega'^2} \tag{1}$$

where, the *nth* harmonics extracted is called *tr*, the control gain is called *k*, the error signal is called ε, the resonance frequency is called ω'.

The two in-quadrature output signals and the input signal of the adaptive filter in Fig.1, i.e. *tr*, *qd* and *ref*, are defined by the following transfer functions:

$$Tr(s) = \frac{tr}{ref}(s) = \frac{k\omega' s}{s^2 + k\omega' s + \omega'^2} \tag{2}$$

$$Qd(s) = \frac{qd}{ref}(s) = \frac{k\omega'^2}{s^2 + k\omega' s + \omega'^2} \tag{3}$$

As can be concluded from (2), the bandwidth of the band-pass filter is exclusively set by the gain *k* and is independent of the center frequency ω'. It is the same for the low-pass filter of (3), in which the static gain only depends on *k*. The effect of the gain *k* in the frequency response of the adaptive is clearly shown in the Bode diagrams of Fig.2.

From the equation in (2), the time response of SOGI-QSG for a given sinusoidal input signal $ref = A\sin(\omega t)$ is described by [10]:

$$tr = -\frac{A}{\lambda}\sin(\lambda\omega t)\cdot e^{-\frac{k\omega'}{2}t} + A\sin(\omega t) \tag{4}$$

$$qd = A\left(\cos(\lambda\omega t) + \frac{k}{2\lambda}\sin(\lambda\omega t)\right)\cdot e^{-\frac{k\omega'}{2}t} - A\cos(\omega t) \tag{5}$$

where, $\lambda = \sqrt{4-k^2}/2$, and $k < 2$.

As can be concluded from formulas (4) and (5), the output signals, i.e. *tr* and *qd*, are composed of the transient part and the steady-state part. When the system tends to be stable, $e^{-\frac{k\omega'}{2}t} \to 0$, we can further conclude:

$$tr \to A\sin(\omega t) \tag{6}$$

$$qd \to -A\cos(\omega t) \tag{7}$$

According to the above two formulas, the phase of the input signal can be obtained, which can be expressed as:

$$\varphi = \omega t = \arctan(\frac{tr}{-qd}) \tag{8}$$

When the system tends to be stable, the accurate phase can be obtained by the formulas (6)-(8). Therefore, the obtained phase by this method is the steady phase, which is especially suitable for the steady-state analysis of the single-phase-to-ground fault waveform of the neural system.

2.2. Principle of Phase Difference Location

When the metallic grounding takes place in the C phase, the A phase voltage becomes $U_A^{'} = U_A - U_C$, which can be expressed as:

$$\begin{aligned} U_A^{'} &= U[\sin(\omega t) - \sin(\omega t - 120^0)] \\ &= \sqrt{3}U\sin(\omega t + 30^0) \end{aligned} \tag{9}$$

Likewise, the voltage of B phase becomes $U_B^{'} = U_B - U_C$, which is specifically expressed as:

$$\begin{aligned} U_B^{'} &= U[\sin(\omega t + 120^0) - \sin(\omega t - 120^0)] \\ &= \sqrt{3}U\sin(\omega t + 90^0) \end{aligned} \tag{10}$$

At this point, the zero sequence voltage is $U_0^{'} = U_A^{'} + U_B^{'}$ which is sorted and simplified as:

$$U_0^{'} = 3U\sin(\omega t + 60^0) \tag{11}$$

Therefore, the voltage and current vectors after single-phase-to-ground fault are shown in Fig.2.

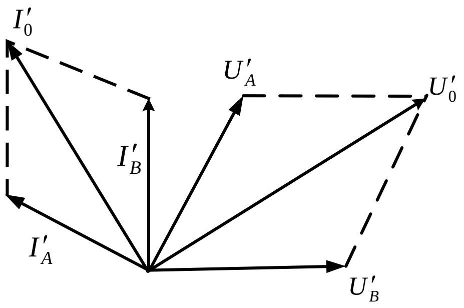

Figure 2. Voltage and current vector diagram after single-phase-to ground fault

In the above figure, I_A' is A phase relative capacitive current, I_B' is B phase relative capacitive current after fault, I_0' is the zero sequence current, U_A' is A phase voltage, U_B' is B phase voltage, U_0' is zero sequence voltage.

When the fault of single-phase metallic grounding occurs, the capacitive current I_0' of non-fault circuit is:

$$\begin{aligned} I_0' &= I_A' + I_B' \\ &= \frac{\sqrt{3}U\sin(\omega t + 30^0 - 90^0)}{X_A} + \frac{\sqrt{3}U\sin(\omega t + 90^0 - 90^0)}{X_B} \\ &= \frac{3U}{X}\sin(\omega t - 30^0) \end{aligned} \tag{12}$$

where, $X_A \approx X_B \approx X$ is the capacitive reactance of single-ground capacitance.

It can be obtained from the above analysis that when the fault of single-phase-to-ground occurs in C phase, the zero sequence current of the non-fault circuit is the vector sum of the relative capacitance current of A and B phases. Their amplitudes are three times as many as the relative capacitance current of the normal system and lead U_A' by 30°. However, the zero sequence voltage lags U_A' by 60°. Therefore, the zero sequence current I' of the non-fault circuit lags the zero sequence voltage U_0' by 90°.

The zero sequence current of fault circuit is the vector sum of the relative capacitive current of A and B phases, which flows from the line to the bus and is opposite to that of the non-fault circuit. Therefore, the zero sequence current lags zero sequence voltage by 90° for the fault circuit. Hence, the fault segment can be located based on the fundamental phase difference between zero sequence voltage and zero sequence current [11]. If the checkpoint is located outside the fault area, the zero sequence current leads zero sequence voltage. Because of the small amount of active component in the zero sequence current, leading phase will be slightly less than 90°. On the contrary, if the checkpoint is located inside the fault area, the zero sequence current lags zero sequence voltage. Because of the small amount of active component, lagging phase will be slightly more than 90°.

According to the phase relationship between the zero sequence current and voltage, for the neutral point ungrounded system, the fault location criterion can be set as follows [1]: If $80^\circ < \angle U_0' \text{-} \angle I_0' \le 110^\circ$, the checkpoint is located inside the fault area; otherwise, the checkpoint is located outside the fault area.

3. Experiment Analysis

3.1. Simulation Experiment

In this paper, the data generated by MATLAB is used as the original signal of the zero sequence voltage and zero sequence current, whose waveforms are shown in Fig.3. The zero sequence voltage leads zero sequence current by 90 degree. The original signal is composed of fundamental harmonic and *5th* harmonic. The amplitude of *5th* harmonic is 20 percent of fundamental harmonic. The fundamental harmonic frequency is 50Hz and the sampling frequency is 4096Hz.

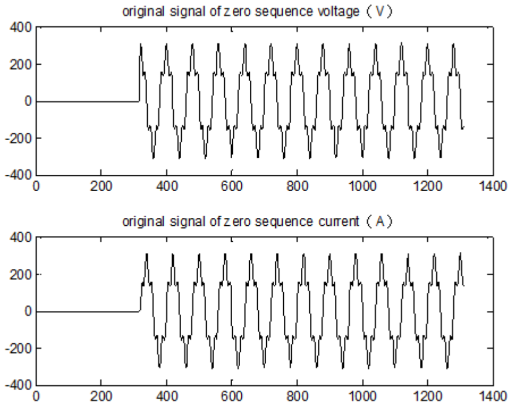

Figure 3. Original signals of zero sequence voltage and zero sequence current

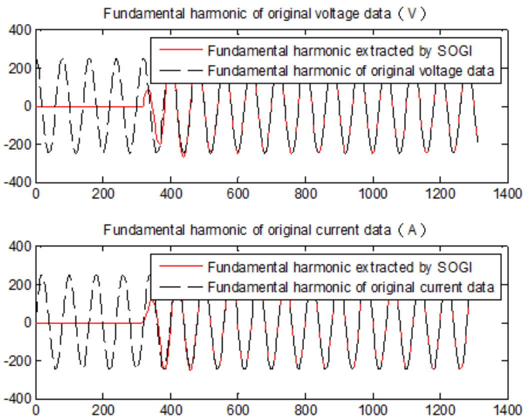

Figure 4. Fundamental harmonics of original data and extracted by SOGI

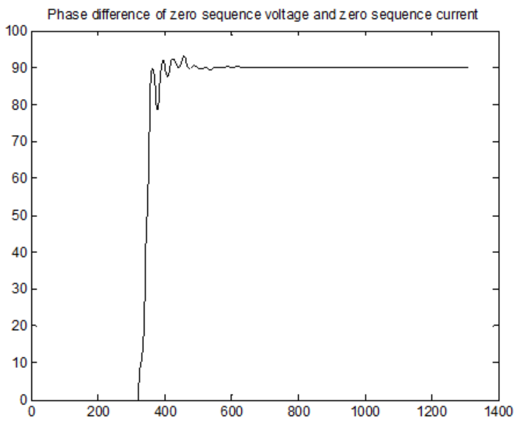

Figure 5. Phase difference between zero sequence voltage and current extracted by SOGI

The fundamental harmonics extracted by SOGI are shown in Fig.4. Compared with the fundamental component given in the original signal, the extracted results are accurate. The phase difference between zero sequence voltage and zero sequence current is shown in Fig.5.

As can be seen from the Fig.5, there is a sudden change at about the *320th* point. After the *420th* point, the phase difference between zero sequence voltage and zero sequence current is about 90 degree. It is consistent with the original signal, which proves that the phase extraction method proposed in this paper is feasible.

3.2. Verification of Actual Data

The actual data is used to test the proposed fault segment location method in this paper. At the same time, in order to verify the superiority of the method proposed in this paper, it is compared with the Euler-based phase extraction method. In order to fully test the phase extraction method in this paper, the actual field data is selected to verify the method. The actual waveform of zero sequence voltage and zero sequence current is shown in Fig.6.

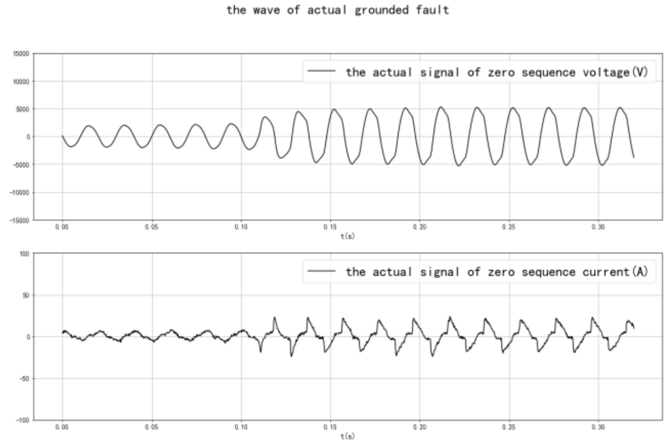

Figure 6. Actual zero sequence voltage and current waveforms

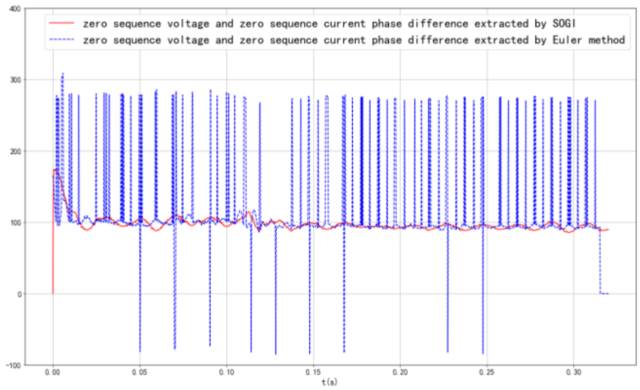

Figure 7. Comparison of phase difference extracted by SOGI and Euler

As can be seen from Fig.7, the phase difference between the zero sequence voltage and zero sequence current remains the same, which means that the zero sequence voltage leads the zero sequence current by about 100 degree. Then according to the phase difference location principle, it can be determined whether the segment of this checkpoint is fault segment.

Moreover, as can be seen from Fig.7, the extracted phase difference based on SOGI is basically stable at about 100°. However, the extracted result based on traditional Euler fluctuates widely. As a conclusion, the extracted result based on SOGI is more accurate than that based on traditional Euler method. It also guarantees the accuracy of the fault segment location based on the principle of phase difference theory.

4. Conclusion

Single-phase-to-ground fault segment location method based on SOGI is proposed in this paper. This method extracts the fundamental harmonic phases of zero sequence voltage and zero sequence current by SOGI and then locate the fault segment based on the phase relationship of the two. The test results of simulation data and actual data shows that this method can accurately extract the phase of zero sequence voltage and zero sequence current and then locate the fault. The main contribution of this paper lies in: The SOGI is firstly applied to small current ground fault location. It is used to extract the phases of zero sequence voltage and zero sequence current. Compared with the phase extraction method based on Euler method, the designed method of this paper is more accurate, which also ensures the accuracy of the fault segment location based on phase difference theorem.

5. References

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