A Fault Line Selection Technique for Single-Phase-to-Earth in network grounded with Arc Extinguishing Coil

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Abstract. For the fault line selection of single-phase-to-earth network, the instantaneous characteristic of the arc extinguishing coil is worth expecting. Focused on the transient characteristics in fault line selection technique, the sinusoid adaptive filter (SAF) and the sinusoid approximation of instantaneous signal (SAIS) are adopted in this paper. SAF is used to obtain the grounding moment, while SAIS is applied to obtain the direction and amplitude of the zero-sequence fundamental current when grounding happens. As for eliminating the influence of current transformer (CT) polarity, the compensation feature realized by SAIS is effectively adopted in selecting process. The techniques and methods in the paper have been applied to Chongqing Electric Power Co. for 5 years. In 5 years, hundreds of grounding faulted line has been chosen correctly, 6 wave records of which are shown in the paper.

1. Introduction
For many MV networks in China, it is essential that the operation reliability can be enhanced by arc extinguishing coil grounding, as well as safety of the power distribution system be ensured. However, it is still complicated in selecting the fault line when single-phase grounding fault happens. As for the zero-sequence fundamental current $i_0$ on the fault line, when its direction is the same as that of the non-fault line, its amplitude is less than that of the non-faulty line [1], which leads to disappearance of ground fault characteristic after arc extinguishing coil over-compensated.

Two kinds of methods, aimed at grounded arc-suppression coil, are adopted for selecting fault line. In the first type of method, the increase of zero-sequence current $i_0$ on the fault-line is traced while changing the inductance in circuit where arc extinguishing coil is equipped. The correct rate is ideal, however, it is tough to change the inductance concerned with other major equipment, which will increase operating costs and reduce operational security. As for the second kind of fault line selection method, the grounding fault characteristic rather than the inductance of arc extinguishing coil is mainly concerned. To cope with the disappearance of the fault characteristics of $i_0$, methods based on high frequency components is employed, which can rarely satisfy the selection accuracy after over-compensated [2,3]. At present, the most hopeful method is based on the grounding fault character at $t_0$ ($t_0$ is the moment grounding happens), namely the grounding instantaneous characteristic.

2. Fault Line Selection Based on the Grounding Instantaneous Characteristic
Usually the zero-sequence voltage $u_0$ is quite low before the occurrence of single-phase-to-earth in MV networks. The zero-sequence current $i_0$ in arc-suppression coil is little and will not change suddenly due to inductance, so it is not able to be observed when grounded. As for the fundamental
zero-sequence current \( i_0 \), its direction on the fault-line is from-line-to-bus, and its direction on the non-faulty line is opposed. Also, the amplitude of \( i_0 \) on the fault-line is greater. Therefore, the selecting mechanism can be realized according to the direction and amplitude of \( i_0 \) when grounding happens. Practically, after a single phase grounding occurs, the inductance compensating process in arc-suppression coil is usually finished in 5 ms. Within 5 ms, how to obtain the grounding moment and how to obtain current direction and amplitude are of great importance for selecting fault lines.

2.1. Obtaining the Grounding Moment

Since the compensating process can be very transitory when a single-phase-to-earth occurs, the method of detecting the occurrence of grounding through the zero-sequence voltage amplitude does not perform well. Therefore, the zero-sequence voltage interrupt algorithm is employed to improve the sensitivity. The zero-sequence voltage break arithmetic based on the sampling values between two periods is subject to the disturbances in the sampling values, therefore the sensitivity of the \( t_0 \) is not very high. In this paper, the sinusoid adaptive filter (SAF) is used to obtain \( t_0 \) [4].

Figure 1 shows the principle diagram of SAF. Input signal \( u(t) \) is a fundamental frequency sine function with some disturbance \( \delta(t) \), it can be expressed as:

\[
u(t) = a \cos(\omega t) + b \sin(\omega t) + \delta(t)
\]  

(1)

Referring to expression (1), parameter \( A \) and \( B \) is constructed in the form of sine functions in equation (2):

\[
y(t) = A \cos(\omega t) + B \sin(\omega t)
\]  

(2)

In Figure 1, \( \cos \omega t \) is obtained by phase shift of 90° in \( \sin \omega t \). Subtracting \( y(t) \) from \( u(t) \), the error \( e(t) \) of SAF is gotten, that is:

\[
e(t) = u(t) - y(t)
\]  

(3)

Based on equation (3), adjusting the parameter \( A \) and \( B \) with least square arithmetic to get \( e(t)^2 = (u(t) - y(t))^2 \) minimized for any \( t \) in the domain, so that \( y(t) \) is able to approximate the fundamental frequency sine function in \( u(t) \).

![Figure 1. SA method schematic diagram.](image)

After \( y(t) \) is approximated to the fundamental frequency sine function in \( u(t) \), the value of \( y(t) \) can forecast the value of the fundamental frequency sine function in \( u(t) \) at time \( t \). If input signal \( u(t) \) is a fundamental zero-sequence voltage with some disturbance, \( y(t) \) will be approximated to the fundamental zero-sequence voltage, without including any disturbance. Subtracting the calculating value of \( y(t) \) from the sampling value of \( u(t) \), the error \( e(t) \) is the disturbance in the sampling value. Under normal circumstance, the disturbance is not larger than the threshold of the grounding moment. When single phase grounding occurs in MV networks, the fundamental frequency zero-sequence voltage reflected by the error \( e(t) \) will increase. Therefore, as long as the increase is larger than the threshold value at \( t_0 \), the grounding moment will be obtained. Because \( y(t) \) of SAF is a fundamental
frequency sine function without disturbance, the sensitivity of the grounding moment based on SAF is higher than the zero-sequence voltage break arithmetic. Thousands physical experiments in laboratory and hundreds grounding records in field show that the time of the grounding moment based on SAF is less than 1 ms.

2.2. Solution of Zero-Sequence Current Direction and Amplitude

The direction and amplitude of \( i_0 \) should be obtained in a short time after grounding. Since the zero-sequence current on fault-line is a non-periodic instantaneous signal, and its waveform is tangled and diverse under different grounding fault conditions, which is hard to be solved by Fourier transformation. Although Wavelet transformation can process non-periodic instantaneous signal to some extent, the result is not ideal. SAIS performs well in obtaining the zero-sequence current direction and amplitude after grounding, and its principle diagram is shown in Figure 2.

The input instantaneous signal \( u(t) \) is as follows:

\[
u(t) = A_m(t)\sin(\omega t + \varphi(t)) = a(t)\cos(\omega t) + b(t)\sin(\omega t)
\]

where, \( A_m(t) \) is the instantaneous amplitude at \( t \) moment obtained in equation (6), \( \omega \) is the fundamental angular frequency, and \( \varphi(t) \) is instantaneous initial phase in equation (7).

The mathematic model of sinusoid function, constructed in equation (4), can be expressed with \( A(t) \) and \( B(t) \).

\[
y(t) = A(t)\cos(\omega t) + B(t)\sin(\omega t)
\]

In Figure 2, \( \cos \omega t \) is obtained by phase shift of \( 90^\circ \) in \( \sin \omega t \), and \( e(t) \) is the error which is gotten by subtracting \( y(t) \) from \( u(t) \). By least square arithmetic, \( A(t) \) and \( B(t) \) are adjusted to \( A_e \) and \( B_e \) to ensure \( e(t)^2 = (u(t) - y(t))^2 \) is minimal at any \( t \). When the constructed \( y(t) \) is approximated to the instantaneous signal \( u(t) \), \( a(t) \) and \( b(t) \) in expression (4) can be replaced by the solved \( A_e \) and \( B_e \), so that \( A_m(t) \) and \( \varphi(t) \) can be got in equations (6) and (7).

\[
A_m(t) = \sqrt{A(t)^2 + B(t)^2}
\]

\[
\varphi(t) = \text{arctg} \frac{A(t)}{B(t)}
\]

\[\text{Figure 2. Principle diagram of SAIS.}\]

\( A_m(t) \) and \( \varphi(t) \) can be obtained by SAIS in a short interval (generally 5ms) after grounding. As for the zero-sequence current at \( i_0 \), set as \( i_0 \), the solved instantaneous amplitude can be regarded as the amplitude of fundamental current \( i_0 \). The phase difference between the solved instantaneous initial phase of \( i_0 \) and \( v_0 \) is as the fundamental zero-sequence current direction. As long as the direction and amplitude is obtained, it is not difficult to select the fault line in networks that arc-suppression coils are equipped.

The fault line can be selected by comparing the magnitude of the fundamental zero-sequence
current $I_{f0}$ of each line at $t_0$. If there are more lines in the substation and the zero-sequence ground current is larger, which is common in cities, the amplitude of $I_{f0}$ on the faulty line will be much larger than that on the non-faulty line, so the selection rate of fault lines can be up to 100% in theory.

Also, comparing the direction of $I_{f0}$ of every line at $t_0$, the faulted line can be selected. If the direction of $I_{f0}$ on every line is correct, the correct rate of the fault line selection will be up to 100% in theory. Practically, the correctness of the direction of $I_{f0}$ depends not only on the solving method, but also on the polarity of the zero-sequence CT in field. The polarity of the zero-sequence CT may be wrong due to on-site inspection in the substation, and then fault line selection will fail. In order to obtain more stable results, a selecting method of arc extinguishing coil based on compensation characteristics is proposed.

3. Fault Line Selection Based on the Compensating Characteristic

For the zero-sequence fundamental current $I_{f0}$ on the fault-line, when single-phase grounding, its amplitude usually attenuates, and if the inductive compensation current is greater than the sum of the zero-sequence current on the non-faulted line, its direction will be reversed. In compensating process of arc-suppression coil, the above compensating characteristic is intrinsic to faulted line, but is inexistent to non-faulted line. Therefore, as long as the compensating characteristic after grounding is figured, the faulted line can be chosen, which is not troubled with the polarity checking of the zero-sequence CT.

Compensating characteristic performs well for the fault line selection, however, it is difficult for common methods, such as Fourier transformation and Wavelet transformation. Therefore, SAIS is adopted to obtain the instantaneous amplitudes and the instantaneous initial phases of the zero-sequence current. Then the varying characteristic of the amplitude of $I_{f0}$ can be figured by observing the solved amplitudes at every time $t$. The fault line can be selected by observing the reduction of the amplitude under the compensation process. Also, the varying characteristic of the direction of $I_{f0}$ can be obtained, by using phase differences between solved initial phase of $i_0$ and the initial phase of $v_0$. If the direction is reverse due to compensation, the faulted line can be chosen as well.

4. Application Result in Field

After introducing SAF and SAIS, a fault-line selection method based on the grounding instantaneous characteristic and the compensating characteristic has been realized. With the fault line selection technique in the paper, a fault line selection device was schemed out, which has been applied to Chongqing Electric Power Co. for 5 years. In 5 years, hundreds of grounding faulted line has been chosen correctly by the fault line selection device, 6 wave records of which are shown in Figure 3.
In Figure 3, the x-coordinate is sampling times, ranging from 0 to 30ms, and the y-coordinate is sampling value, ranging from -500V to 500V. The data is obtained at the device sampling-frequency of 1600 Hz. Yellow curve, green curve, red curve denotes sampling-voltage of A-phase, B-phase, C-phase respectively. The sampling zero-sequence voltage on the faulty-line is represented as the white curve, and the sampling zero-sequence current is represented as the blue curve. A fundamental frequency period or 20ms means that the sampling time is 32, so the recording time of the wave records in Figure 3 is one fundamental frequency period (20ms).

Figure 3a is the wave record of a C-phase-to-earth from 2006-09-05 04:10:05 to 2006-09-05 04:10:49 on 619 line of 10kVI bus in Chuqimen substation. In Figure 3a, the zero-sequence current on the faulted line only lasts 5 sampling times (about 3ms), and is almost compensated to zero after 5 sampling times.

Figure 3b is the wave record of an A-phase-to-earth from 2007-11-15 04:06:11 to 2007-11-15 17:36:16 on 649 line of 10kVII bus in Chuqimen substation. In Figure 3b, the compensating characteristic works very well although the zero-sequence polarity of the fault line CT reversed.

Figure 3c is the wave record of an A-phase-to-earth from 2006-09-14 07:27:07 to 2006-09-14 07:27:15 on 614 line of 10kVII bus in Niujiaotuo substation. In Figure 3c, the zero-sequence voltage increases slowly, A-phase residual voltage is higher, so the grounding fault should be an A-phase-to-earth with a resistance. The blue curve which appears in front of the zero-sequence voltage is under under-compensation.

Figure 3d is the wave record of a C-phase-to-earth from 2007-02-20 10:17:00 to 2007-02-20 10:17:01 on 635 line of 10kVI bus in Chuqimen substation. In Figure 3d, C-phase residual voltage is higher, the compensating process with arc extinguishing coil lasts 14 sampling times (about 9ms), and the blue curve is almost equal to zero after compensating.

Figure 3e is the wave record of an A-phase-to-earth from 2007-01-25 22:19:52 to 2007-01-25 22:38:44 on 613 line of 10kVI bus in Chuqimen substation. In Figure 3e, the compensating process

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**Figure 3.** Wave records of single-phase-to-earth in field.
with arc extinguishing coil is larger than 16 sampling times (10ms).

Figure 3f is the wave record of a C-phase-to-earth from 2006-09-06 15:09:19 to 2006-09-06 15:09:56 on 642 line of 10kVII bus in Chuqimen substation. In Figure 3f, the blue carve is under excessive over-compensation, and the compensating current is much greater than the grounding capacitance current.

5. Conclusion

When single-phase grounding occurs, characteristics based on the over-compensation of the arc-extinguishing coil are not very ideal in fault line selection. In addition, due to the complex waveform, it is incredibly difficult to apply ground transient characteristics. Techniques and methods for better fault-line selection are summarized as follows.

1) SAF is used to obtain the grounding moment. The anti-disturbance ability of SAF is stronger, the sensitivity of grounding moment is higher. Thousands physical experiments in laboratory and hundreds grounding records in field show that the time of the grounding moment based on SAF is less than 1 ms.

2) SAIS is adopted to obtain the direction and amplitude of zero-sequence current after grounding. The instantaneous amplitudes as well as phases are calculated by SAIS within a short interval (generally 5ms) after grounding, and then the fundamental frequency zero-sequence current direction and amplitude can be obtained, which will be applied for the next fault line selection implementation.

3) A fault line selection technique based on compensating characteristics is proposed to cope with the zero-sequence CT polarity that determined by the direction of fundamental zero-sequence current. The fundamental frequency zero-sequence current direction and amplitude at every time \( t \) can be obtained by SAIS, the compensating characteristic after grounding is figured, so the fault line selection employed compensating characteristic is achieved successfully.

A fault line selection device that applied the techniques and methods in this paper was schemed out and has been applied to Chongqing Electric Power Co. for 5 years. In 5 years, hundreds of grounding faulted line have been chosen correctly by the fault line selection device, 6 wave records of which are shown in the paper.

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