Analysis of the influence of three-phase asynchronization recording on fault location of distribution network

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Abstract: In order to improve the practical effect of the fault location technology, it is necessary to analyze the error caused by the three-phase asynchronization of the fault indicator recording. The influence of the three-phase recording asynchronization on the fault location of the distribution network is analyzed from the aspects of the start-up criterion, the error level of the zero-sequence current and the zero-sequence voltage. The simulation results show that fault location devices of different principles are affected differently by the asynchronization recording. In order to avoid mistake start-up of the fault location device, the change value should be used to construct the fault location start-up criterion. Meanwhile, the measurement accuracy of transient fault characteristics will be affected to a certain extent by the asynchronization of the fault indicator recording, but it has little effect on the reliability of fault location, and it can even make the fault characteristics more obvious after the single-phase fault occurs.

1. Introduction

The reliability of power supply can be improved by fast and reliable single-phase to ground (SPG) fault location technology [1]. In recent years, a variety of different ground fault location methods have been emerged. According to the different signals used, it can be divided into two categories: active location methods and passive location methods. The former is mainly the signal injection method, which locates by detecting the distribution of the injected signal in the system, but it requires additional equipment, so it is not widely used in the field operation. The latter is based on the characteristics of the voltage and current signals generated by the fault to determine the fault point, including impedance method [2], zero sequence current comparison method, three-phase asymmetric method [3-4], harmonic analysis method [5] and correlation coefficient method [6] using transient fault characteristics, and so on. The above methods are widely used in SPG fault location, and the certain results have been achieved.

The field application of the location method relies on accurate fault recording information. In resonant grounding system, the transient fault characteristics are more obvious, meanwhile, the economic benefits can be obtained by the operation of the fault indicator in a short time [7], therefore, the transient recorder type fault indicator is widely used in distribution networks. In [8], when a SPG fault occurs in a 10kV distribution network, there are still false alarms and omissions in the field fault indicator and the accuracy of field fault location still needs to be improved. It is also an important
research content of electric power companies and related enterprises to analyze the reasons for the abnormal operation of existing fault location devices. The small time difference of the three-phase asynchronization of the fault indicator will introduce a large measurement error. When the measurement error is superimposed with the error caused by other factors such as the transformer error, it may cause the fault indicator to operate incorrectly, which will directly affect the accuracy of the fault location [9].

Firstly, based on the fault indicator principle of the fault location system [10], the reasons for the error of the collected phase current and phase voltage when the sampling of the three-phase fault indicator is not synchronized, and the influence of the error on the calculation result of the zero-sequence current are analyzed in this paper. Secondly, the 10 kV neutral non-effectively grounded system is established to simulate the zero-sequence current waveform synthesized by the recording device when a SPG fault occurs. In terms of different fault location methods, the error level and location reliability of each fault indicator start-up and location criterion when the three-phase sampling of the fault indicator is not synchronized are analyzed.

2. The asynchronization of fault indicator three-phase recording

The reason for the asynchronization of the three-phase recording of the fault indicator is the synchronization error during normal operation and the broadcast error after starting the fault location. According to the design requirements of the fault indicator, the synchronization error of the acquisition unit shall not be greater than 100μs [11]. The zero-sequence current waveform required for fault location is obtained through three-phase waveform superposition, and the synthesis principle is shown in Fig. 1.

Fig. 1 Principle of Synthesizing Transient Zero-sequence Current in Fault Recording

When the distribution network is in normal operation, the operating parameters and zero sequence components of each phase are measured and calculated in real time by the fault indicator.

When a SPG fault occurs, if the signal measurement value exceeds the action setting value, the fault indicator is activated, and the fault location procedure is entered according to the start criterion. For the selected fault location method, it is necessary to record the voltage and current of each phase of the power grid in real time. The recording range is no less than 4 cycles before the start and 8 cycles after the start of the fault indicator, and there are no less than 80 sampling points per cycle [12].

The fault indicator exists two states: sleeping and accepting. Due to the economic constraints of operation, the three-phase fault indicator is not always in the accepting state. When a phase is faulty and the synchronous broadcast is sent to the other two phases, if the fault indicators of the other two phases are in the sleeping state, there will be a delay Δt in the recording. The recorded waveform the non-faulty phase uploads with the delay Δt, which results in the broadcast error in the measurement error [9].
3. The influence of the unsynchronized recording on the starting criterion

When a SPG fault occurs in the system, the recording-type fault indicator can be started by a sudden drop in the fault-to-ground voltage; the grounded fault can be reflected by the zero-sequence voltage and current. Based on the zero-sequence current change, the fault indicator starts to record, which is used to distinguish load fluctuations and grounded faults. The following analyzes the impact of the three-phase asynchrony caused by the timing error on the above three starting criterion.

3.1. Low voltage start-up

When a SPG fault occurs in the distribution network, the magnitude of the fault current is extremely small, so the start-up accuracy by the fault current is low. Generally, the obvious feature of the voltage drop of the fault phase is used to select the fault phase at the same time. The electric field strength can be measured by the acquisition unit installed on the three-phase line, respectively, to obtain each phase-to-ground voltage. When the system is faulty, the voltage of a certain phase drops below 20%, triggering all signal recordings, the three-phase voltage is independently judged, the start of the fault indicator is not affected by the three-phase asynchronous recording.

3.2. Zero-sequence current and voltage start-up

For the devices started by zero-sequence current, if the zero-sequence current exceeds the threshold, the fault indicator will start. Due to synchronous precision, when the three-phase fault indicator is not synchronized to record, it will affect the magnitude of the zero-sequence current.

When all loads are three-phase balanced loads, the influence of the timing error on the collected data of the power frequency fault detection device is analyzed during normal operation. If the timing error is 100μs, the corresponding recording phase deviation is 1/100×180°=1.8°. At this time, the B and C phase voltage recording waveforms will have a phase shift of 1.8°, accounting for 1% of the entire cycle. The three-phase power frequency synthesized zero sequence current in normal operation is shown in (1)

\[3i_0 = i_{0} + i_{-120°} + i_{120°} = 0\text{A}\] (1)

In the case of synchronous precision, A phase is used as a reference, B, C phase are opposite to A phase, respectively, the B phase angle range is [-121.8°,-118.2°]; the C phase angle range is [118.2°, 121.8°]. According to the phasor analysis, the phase B leads (or lags) 1.8°, and the phase C lags (or leads) 1.8°. At this time, the zero sequence current obtained by the superposition of the three-phase currents in normal operation is

\[3i_0 = |i_{0°} + i_{-121.8°} + i_{121.8°}| = 0.055i = 5.5\%i\] (2)

The waveform diagram of phase A current during normal operation and the waveform diagram of zero sequence current under the synchronous error of 100μs are shown in Fig. 2.

![Fig.2 The waveform diagram of phase A and zero sequence current under the synchronous error of 100μs](image)
According to the simulation recording data, it can be obtained that when the synchronous precision exists, the rms of the synthesized zero sequence current is about 6.27% of the rms of the phase current, that is, the synthesized zero sequence current is not zero during normal operation. Therefore, if the starting criterion setting value is set to 10% of the phase current, due to factors such as current transformer measurement errors and harmonics during operation, and the need to superimpose unbalanced zero-sequence currents, it may be triggered by mistake during normal operation or multiple triggers when a continuous transient ground fault occurs, which results in a decrease in the accuracy of fault location.

For devices that are started by zero-sequence voltage, the measurement methods are: first, measuring the open voltage of the delta-connected transformer; second, a special zero-sequence voltage transformer is installed on the line. Therefore, the zero-sequence voltage measurement is not affected by synchronous precision.

3.3. Zero-sequence current change start-up
In the case of stable load, any sampling time meets the formula (3):
\[
\Delta 3i_0 = \left| \sum_{i=a,b,c} i_i(t) - \sum_{i=a,b,c} i_i(t-T) \right| = 0
\]
(3)

In the formula (3), \(i_i(t)\) is the current sampling value of each phase at a certain time; \(i_i(t-T)\) is the current sampling value of one cycle earlier. When a ground fault occurs, the current change of the non-faulty phase is smaller and the change of \(3I_0\) is larger. The zero sequence current change start-up criterion is
\[
|\Delta 3i_0(t) - |\Delta 3i_0(t)| > 0
\]
(4)
\[
|\Delta 3i_0(t) - |\Delta 3i_0(t)| > 0
\]
(5)
\[
|\Delta 3i_0(t) - |\Delta 3i_0(t)| > 0
\]
(6)
\[
|\Delta 3i_0(t)| > \beta I_N
\]
(7)

\(I_N\) is the secondary rated phase current. The influence of zero-sequence mutual impedance and the recording error when adjacent parallel lines are grounded are taken into account in the setting of \(\beta\). However, considering that the fault characteristics of the neutral non-effectively grounded systems are not obvious, the setting value is generally smaller. When the three-phase of the fault indicator are fully synchronized, the synthesized zero-sequence current in normal operation is shown in the formula (1).

When there is a synchronous error of 60μs between phase B, phase C and phase A, the unbalanced current will be measured by the zero sequence current filter.
\[
3I_0 = I \angle 0^\circ + I \angle -118.92^\circ + I \angle 121.08^\circ
\]
\[
= 0.019I \angle -89.46
\]
(8)

At this time, the zero-sequence current component is used as the starting criterion, which will be a large error. If the synchronization error remains the same, \(3i_0(t)\) and \(i_i(t)\) are measured. The method of zero-sequence current change start-up is used to avoid mistake start-up caused by load fluctuations, and it is not affected by the three-phase asynchronization of the fault indicator.

4. Simulation Analysis

4.1. Simulation Analysis of Voltage Characteristic Error
The SPG fault occurrence time is set to 0.04s, phase B and phase C have 100μs synchronization error with phase A respectively, and there is a maximum unbalanced voltage. The error level of the transient zero-sequence voltage before and after the fault is shown in Fig. 3.
During normal operation, the zero-sequence voltage should be 0V, but the error of the zero-sequence voltage measurement is about 1%~2% of the phase voltage due to the three-phase asynchronization of the fault indicator. As shown in Fig. 4 after a fault occurs, the maximum error of the zero-sequence voltage in the transient state can reach 22% of the phase voltage. Therefore, when the three-phase sampling is not synchronized, the synthesized zero-sequence voltage amplitude has a large error in the transient state, which will affect the accuracy of the synthesized transient signal.

4.2. Simulation Analysis of Current Characteristic Error
Matlab/Simulink is used to build a typical 10kV distribution network model with five outgoing lines to analyze the asynchronous error of the three-phase fault indicator, the constant load of each line is 1MW+0.2MVar.

The simulation results show that the zero-sequence current measurement value is not zero because the three-phase fault indicator is not synchronized in time, that is, a very small unbalanced current. When there is no synchronization error and the synchronization error is 60μs, the zero-sequence current waveforms are shown in Fig. 4. As the synchronization error changes, the size and phase of the unbalanced current will change, that is, when the synchronization error increases, the unbalanced current will increase.

When a SPG fault occurs, the frequency of the transient component is higher, and the influence of the phase shift of the waveform caused by the synchronization error is more significant than that of the steady state. When the three-phase fault indicator does not measure synchronously, the influence degree of the zero sequence current on the fault location criterion is analyzed. The fault occurrence time is set to 0.04s, phase B and phase C have 100μs synchronization errors with phase A. Fig. 5 depicts the comparison result of the zero-sequence current waveform of the faulty line and the zero-sequence current waveform of the three-phase asynchronization recording under the fault condition.
Fig. 5 Comparison of synchronous and asynchronous synthesized zero-sequence current waveforms when a SPG fault occurs

Fig 6 depicts the error level of the difference between the two waveforms. It is obtained that the synthesized error of the zero-sequence current during normal operation and steady state after a fault is about 5% of the zero-sequence current, and the transient peak error of the zero-sequence current can reach 15% of the zero-sequence current. However, the transient slope error for measuring waveform distortion is only 3%.

Fig. 6 Three-phase asynchronization zero-sequence current error level

The simulation waveform of the fifth harmonic without synchronization error and synchronization error of 60μs is shown in Fig. 7:

Fig. 7 5th harmonic waveform and error level after a SPG fault occurs
The harmonic characteristics are obvious in the transient process after a fault. High-order harmonic components can be obtained by filtering the transient waveforms collected by the fault indicator. Generally, the 5th-order harmonic characteristics are extracted for fault location. If the synchronization error is 60us, the phase deviation of the corresponding fifth harmonic is \(5 \times 6 / 1000 \times 180^\circ = 5.4^\circ\), the deviation of the phase will be much larger than the error level of the fundamental wave, but the time-domain waveform error will not be obvious after the three-phase superposition. The three-phase sampling of the fault indicator is not synchronized, which increases the amplitude of the zero-sequence current and the content of the 5th harmonic. Therefore, the fault characteristics are more obvious when the SPG fault occurs.

4.3. The Influence of Asynchronous Recording on the Method of Fault Location

The transient signal required for fault location is recorded at a higher speed. After the waveform file reported by the fault indicator are collected by the main distribution automation station, the fault section can be judged by comparing the similarity and difference of these recorded waveforms.

The specific application of the fault location criterion based on the fault indicator is: correlation coefficient method, zero-sequence current amplitude method, transient zero-sequence power direction method, transient zero-sequence current direction method, etc. According to the analysis of the recording error of the fault criterion, the influence of the three-phase asynchronization of the fault indicator on the results of different location principles are shown in Table I.

| Fault location method | The degree of influence on the accuracy of the criterion | Whether affect the result of fault location or not |
|-----------------------|--------------------------------------------------------|-----------------------------------------------|
| Correlation coefficient method | Less affected | No |
| \(I_0\) magnitude method | Error 5% | No |
| Transient zero sequence power direction method | No | No |
| Transient \(I_0\) direction method | Yes | No |

Based on the similarity of the recorded waveforms of the zero-sequence current flowing through the upstream and downstream of at the fault point, the correlation coefficient method is used to judge the fault section. Since the zero-sequence current is hardly affected by the three-phase asynchronization recording, the fault location result is not affected by the three-phase asynchronization recording.

The zero-sequence current magnitude method is applied to the neutral non-effectively grounded system, the zero-sequence current of two adjacent measuring points is used to judge the fault point. When the three-phase recording of the fault indicator are not synchronized, the amplitude of the zero-sequence current of each monitoring point of the fault line will generally increase by 5%, and the amplitude of the zero-sequence current of each monitoring point of upstream at the fault point will be greater than that of the other monitoring points. Therefore, the fault characteristics are more obvious, which will not affect the fault location results.

The transient direction method is that the characteristics of the derivative of the transient zero-sequence voltage and the polarity of the zero-sequence current is used to locate the fault. The waveform of the zero-sequence current and zero-sequence voltage are not affected by the three-phase asynchronization recording, that is, the fault location method is not affected by the three-phase asynchronization recording.
5. Conclusion
The fault indicator is simulated to record asynchronously in this paper, the measured zero sequence voltage and zero sequence current are not 0 during normal operation, whose values are affected by the synchronization precision. The fault indicator is affected by this error and other disturbances, which causes the zero-sequence voltage to exceed the start-up threshold and results in malfunction of fault location. Therefore, the variation should be selected as the fault start criterion as far as possible to reduce the influence of the recording error caused by the three-phase asynchronization.

Meanwhile, the amplitude of the transient zero-sequence current and voltage waveform are amplified by the three-phase sampling asynchronization after the fault, especially the transient zero-sequence voltage, but the waveform of the fault recording is not affected, therefore, the fault location of the fault indicator is almost unaffected. The above conclusions provide basic reference data for the research on the abnormal movement mechanism of the fault indicator, and are of great significance to further improve the operation effect of the fault location equipment in the distribution network.

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