Small current ground fault location method based on Hilbert transform

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Abstract. A new method for small current grounding system single-phase-to-grounding fault location used transient component and Hilbert transform is proposed. The feeder terminal unit detects zero-mode current and line voltage signals, first, perform the Hilbert transform on the transient line voltage, then multiply the line voltage after the Hilbert transform with the zero-mode current, defined the product as fault direction parameter. The FA master determines the line segment where the fault point is located based on the characteristics of the opposite polarity of the front and rear direction parameters of the fault point. The results of digital simulation prove that the proposed method has certain feasibility.

1. Introduction

Non-solidly earthed systems are used for low and middle voltage distribution network in our country. The distribution network has complex structure and many branches. When single-phase-to-grounding fault occurs, because of the current signal is not obvious, so the single-phase-to-grounding fault location technology is difficult to achieve, which may easily lead to accident expansion and affect power supply reliability. After years of research and development, a variety of positioning methods have been proposed, but there are many difficulties and limitations in practical use. The positioning method based on artificial intelligence technology [1,2] can overcome the misjudgment caused by information distortion, and the fault tolerance performance is better, but the upload information is mostly a single direction identifier, the reliability of the signal is not distinguished, and the utilization of the feature information is not enough. The impedance [3] and the traveling wave method [4,5] are mainly applied to the single-phase-to-grounding fault problem of high voltage transmission lines, and are not effective when applied to a distribution network. The signal injection method [6,7] has good results used in the field, but it needs to be equipped with signal injection equipment, which has large investment, long positioning time, and is not good for transient faults and intermittent arc ground faults. Although the correlation method does not need to measure the line voltage, the communication data transmission amount is large, and the synchronization requirement is high.

The feeder terminal unit (FTU) is used for detection voltage and current signals, and the fault zone positioning realized by the feeder automation (FA) system. Most of FTUs are equipped with line voltage transformers that provide voltage measurement signals while powering the FTU [8]. In this paper, a positioning method used transient voltage and zero mode current is proposed. FTU uses the zero-mode current and transient voltage to calculate the fault direction parameters and uploads them to the FA control main station. The main station has the opposite polarity according to the direction of the two sides of the fault section. The feature locates the fault section. The method uses a convenient
line voltage signal, it does not need to add equipment, and the investment is small and easy to implement, and has high practical value.

2. Transient Characteristics Analysis of Small Current Ground Fault

There is an obvious transient process in the ground fault. The transient current generated by the fault is several times larger than the steady-state signals. The location method used the transient informations are highly sensitive. In order to facilitate the analysis of transient processes, the Karenbauer transformation is usually used to transform the three-phase system into a 0,1,2 modulus system without coupling, where the 1,2-module is called the line mode, zero. The modulus component is equivalent to the zero sequence component of the symmetrical component transform [9].

In the characteristic frequency band, the zero-mode input impedance at each detection point distributed along the line is capacitive, and the zero-mode current has the same characteristics [10]. Since the grounding resistance is generally small, the influence produced by the coil can be ignored in the transient period after the fault, and the distribution characteristics of zero-mode current is shown in the Fig. 1. In the figure: C1, C2 are ground capacitance of line l1, l2; The fault occurred at point F on line l3; A, B, C are the section switch mounting points; Q means the end of the line; C1, C2, C3, C4 are the ground capacitance of section AB, BF, FC, CD; zero-mode current \( i_1 = i_{C2} + i_{C1} + i_{B} + i_2 \), \( i_2 = i_{C3} + i_{C4} \).

The zero-mode current sensed by the sound line detection point is the capacitance current to the ground from the detection point to the end of the line, and the direction flows from the bus line to the end of the line. The zero-mode current sensed by the downstream detection point of the fault point also the capacitance current to the ground of the line between the detection point and the end of the line. The fault current from the fault point upstream to the busbar is equal to the sum of the capacitance currents of all the healthy lines and the fault point to the bus line, and the direction flows from the fault point to the busbar, and is opposite to the line zero mode current under the sound line and the fault point/ Assume that phase A has a single-phase-to ground fault problem in system, According to the boundary conditions of the fault point.

\[
\begin{align*}
\sum_{i=0}^{1} i_i &= 0 \\
i_0 &= i_1 = i_2 = \frac{1}{3} i_u
\end{align*}
\]

Where: \( i_0, i_1, i_2 \) are the 0, 1, 2 mode current of fault points respectively; \( i_u \) is the A phase ground current. It can be known from equation (1) that when a small current is grounded, the equivalent is 0, 1, and 2 mode networks are connected in series, and the equivalent model is shown in Fig. 2. Since the impedance of the inductor and the resistor in the 1 and 2 mode networks is much smaller than the capacitive reactance of the distributed capacitor, the equivalent capacitance of the 1 and 2 mode networks is ignored in the figure, and only the influence of the series inductance and the resistance is considered. In the figure: \( C_0 \) is the zero-mode capacitances; \( L_0, L_1, L_2 \) are 0, 1, 2
mode loop inductance, \( L_1 = L_2, R_0, R_1, R_2 \) are 0, 1, 2 mode loop resistance, \( R_1 = R_2, R_f \) is ground resistances; \( u_0, u_1, u_2 \) are the 0, 1, 2 mode voltage.

\[
\begin{align*}
R_0 + L_1 \frac{di_0}{dt} + \frac{1}{C_0} \int_i i_0 dt &= U_f \\
\end{align*}
\]

In the formula:
\[
R_f = R_0 + R_1 + R_2 + 3R_f, L = L_0 + L_1 + L_2, U_f = U_w \sin (\omega t + \phi)
\]

Let \( \delta = R / (2L) \), \( \omega_0 = 1/ \sqrt{LC_0} \), according to formula (2) obtain the following transient zero mode current [11]:

\[
i_{0t} = U_w \omega_0 C_0 e^{-\omega_0 t} \left[ \frac{\omega_0}{\omega} \sin \phi \sin (\omega t) - \cos \phi \cos (\omega t) \right]
\]

In t formula (3): \( \omega_f = \sqrt{\omega_0^2 - \delta^2} \), the transient line mode voltage is:

\[
u_1 = \approx u_2 = L_i \frac{di_0}{dt} + R_0 i_0 = (R_i - L_0 \delta) i_0 + L_0 \omega_0 C_0 e^{-\omega_0 t} \left[ \cos \phi \sin (\omega t) + \frac{\omega_1}{\omega} \sin \phi \cos (\omega t) \right]
\]

It can be seen from \( [R_i - L_0 \delta] / \omega \ll L_i \) and \( [R_1 - L_0 \delta] / \omega \ll L_1 \omega_f / \omega \) that \( (R_i - L_0 \delta) i_0 \) have little effect on \( u_1 \) and \( u_2 \) in the formula (3). Because \( \cos(\omega t) = \sin(\omega t + 90^\circ) \), \( \sin(\omega f t) = -\cos(\omega f t + 90^\circ) \) compares the transient line mode voltage with the transient zero mode current expression, \( u_{1t} \) and \( u_{2t} \) approximate the \( i_{0t} \) 90° phase angle under each frequency component. Converted by Karrenbauer:

\[
\begin{align*}
u_{abt} &= u_{at} - u_{bt} = 3u_{1t} \\
u_{act} &= u_{at} - u_{ct} = 3u_{2t}
\end{align*}
\]

In the formula: \( u_{ab}, u_{ac} \) are transient line voltages; \( u_{at}, u_{bt}, u_{ct} \) are transient three-phase voltages. Thus, the transient line voltages \( u_{at}, u_{bt}, u_{ct} \) are approximated by the transient zero mode current \( i_{0t} \) 90° phase angle under each frequency component. Similarly, when phase B is grounded, it approximates the phase angle of \( i_{0t} \) 90°, and when phase C is grounded, it approximates the phase angle of \( i_{0t} \) 90°.

2.1. A subsection Fault Determine conditions

If a single-phase-to grounding fault occurs in the system, the line voltage will produce a transient component, but its power frequency rms value will remain basically unchanged. The line voltage sudden change can be monitored as the starting condition, and the fault is confirmed by calculating the transient and power frequency effective values.
The starting condition of the line voltage sudden change is:

\[ \Delta u_{st}(t) = \left| u_{st}(t + \lambda) - u_{st}(t) \right| > \zeta \]  

(6)

In the formula: \( u_{st}(t) \) is the sampling value of the line voltage at a certain time; \( \lambda \) is the time interval; \( \zeta \) is the set threshold, generally can be selected as 15% of the system line voltage amplitude. For any line voltage, when equation (5) is established, the fault confirmation process is initiated. First, calculate the effective value \( U_{st} \) of the transient component of the line voltage in the transient period.

The transient period can generally be 2.5~10ms. When any line voltage satisfies \( U_{st} > \zeta \) and the line voltage effective value of each line is substantially the same as in the healthy state, it can be judgment that a single-phase-to-grounding fault has occurred. Otherwise, it is considered to be disturbed and the positioning calculation is not started.

2.2. Fault phase Determination

According to the formula (5) that when the phase A is grounded, the transient line voltage \( u_{sto} \approx u_{stc} \), therefore \( u_{sto} = u_{sto} - u_{sto} \approx 0 \). That is, if a single-phase-to-grounding fault occurred in the system, the two line voltages between the fault phase and the healthy phase have a transient component, and the line voltage transient component between the two healthy phases is substantially zero. Based on this, the criteria for setting the fault phase are: 1) if \( U_{sto} > U_{stc} \) and \( U_{stc} > U_{sto} \), phase A is grounded; 2) if \( U_{stc} > U_{sto} \) and \( U_{sto} > U_{stc} \), phase B is grounded; 3) if \( U_{sto} > U_{stc} \) and \( U_{stc} > U_{sto} \), phase C is grounded.

Where \( U_{sto} \), \( U_{stc} \), \( U_{stc} \) are the effective values of the transient line voltage \( u_{sto} \), \( u_{stc} \), \( u_{stc} \) in the transient process. When any phase of the system is grounded, there are two related transient line voltages that can be used for fault location calculation. For the sake of uniformity, the following can be specified: 1) When phase A is grounded, the transient line voltage \( u_{sto} \) is selected; 2) When the B phase is grounded, the transient line voltage \( u_{stc} \) is selected; 3) When the C phase is grounded, the transient line voltage \( u_{stc} \) is selected.

2.3. Fault direction algorithm

Use \( u_{st}(t) \) to indicate the selected transient line voltage. On the downstream of the single-phase-to-grounding fault point and the sound line, the zero-mode current measurement reference direction is same as the actual flow direction, and the measured transient line voltage \( u_{st}(t) \) leads the transient zero-mode current 90° under each frequency component. At each FTU from the single-phase-to-grounding point to the bus bar, the zero-mode current measurement reference direction is opposite to the actual flow direction, and the measured lag transient zero mode current is 90°. The Hilbert transformer is an all-pass filter with amplitude-frequency characteristics of 1, positive-frequency components for \(-90°\) shift, and negative-frequency components for \(+90°\) shift [12]. The Hilbert transform of the transient line voltage is:

\[ u_{st} = u_{st} \frac{1}{\pi t} \int_{-\infty}^{\infty} \frac{u_{st}}{t - \tau} d\tau \]  

(7)

The fault direction parameter P is defined as the average value of the product of the transient line voltage after the Hilbert transform and the transient zero mode current in the transient period T:

\[ P = \frac{1}{T} \int_{0}^{T} u_{st}(t) u_{st}(t) dt \]  

(8)
It can be seen from the Hilbert transform property that $\hat{u}_{xy}(t)$ is the result of 90° shift of $u_{xy}(t)$, then the $\hat{u}_{xy}(t)$ and $i_w$ of the FTU downstream of single-phase-to-grounding point and the sound line have same polarity, the direction parameter $P>0$; the FTU of the fault line upstream to the bus line at the same time, $\hat{u}_{xy}(t)$ and $i_w$ are reverse polarity, and the direction parameter is $P<0$.

2.4. Fault Location Principle

If a single-phase-to-grounding fault occurred, the direction parameter $P$ calculated by the FTU on both sides of a certain section line can be used to determine whether the section is a faulty section: if the direction parameters of the FTU calculated by the two sides are the same, the fault point is in the section. In addition, the section is a non-faulty section; if the direction parameters of the FTU calculated by the two sides are opposite, the single-phase-to-grounding point between the two sides of the FTU, determine the section is the faulty section. In practical applications, the positioning master station (FA master station) receives the direction parameter uploaded by the FTU (including the remote terminal unit (RTU) in the substation), and confirms that single-phase-to-grounding fault has occurred in the system, and initiates the fault location process. First, the line that determines the direction parameter $P<0$ at the first FTU is the fault line. If the CT polarity is reversed, $P<0$ at the first FTU of multiple lines may occur. In this case, the line with $P<0$ and the largest absolute value is the fault line. Then analyse the direction parameters of other FTUs on the faulty line to determine the faulty section. If the second FTU is $P>0$, the line between the first and second FTU is the faulty section; otherwise, the section is a non-faulty zone. Segment, continue to analyse the direction parameter of the third FTU backwards. By analogy, until the first PTU of the $P>0$ is found, the line segment between the FTU and the previous FTU is the faulty segment. When all FTUs on the faulty line have $P<0$, the fault point is at the end of the line.

The FTU far from the fault point may not start due to the small amount of sudden change, but it does not affect the start of the FTU near the single-phase-to-grounding point and the calculation of the fault parameters, and has no effect on the positioning. For the case where the FTU is accidentally started due to disturbance, the primary station can ignore this information and confirm the single-phase-to-grounding fault has not occurred. In practical applications, it can be used together with the small current grounding line selection device to form an integrated line selection and positioning system. The positioning main station receives the report information of the line selection device, performs positioning on the basis of accurately selecting the fault line, and improves the fault location accuracy.

3. Organization of the Text

3.1. Digital Simulation

Digital simulation verification was carried out using electromagnetic transient simulation software PSCAD. The model is established as distributed parameter type by using the standard parameters of overhead lines, the model is shown in Figure 3. Assuming the single-phase-to-grounding fault occurs in the BC section, and the simulation model line parameters are: positive sequence impedance is $Z_1 = 0.38 + j0.17$ Ω/km, and the positive sequence to ground admittance is $b_1 = 4.045$ μs/km, zero-sequence impedance is $Z_0 = 0.33 + j1.70$ Ω/km, zero-sequence admittance is $b_0 = 2.104$ μs/km, and the equivalent load impedance of each line is unified. Choose $Z = 380 + j40$ Ω. When simulating the arc suppression coil grounding system, the phase A as the fault phase, the arc suppression coil is overcompensated, the overcompensation degree is 8%, the simulation step is 1μs, and the model sampling frequency is set to 100kHz. The recorded waveform of a fault simulation is shown in Figure 4.
When the grounding resistance is 5 and different voltage initial phase angles are set for simulation, the fault direction parameters of each detection point of the arc suppression coil compensation system are shown in Table 1. If the initial phase angle of the voltage is 90°. When the grounding resistance is different, the fault direction parameters of each detection point of the arc suppression coil compensation system are shown in Table 2.

**Figure 3. Simulation model of single phase grounding fault**

It can be seen from the simulation results that the method can accurately locate small current ground faults that occur at different times and different grounding resistances.

The results calculated by equation (8) for each simulation are as follows:

**Tab.1** Direction parameter of different voltage angles in compensation system

| Phase angle/(°) | \( P_A \)  | \( P_B \)  | \( P_C \)  | Result         |
|----------------|------------|------------|------------|---------------|
| 30             | -710.7     | -1029.0    | 107.4      | BC Section    |
| 45             | -1268.7    | -2804.3    | 211.3      | BC Section    |
| 60             | -2002.1    | -4317.4    | 260.1      | BC Section    |
| 90             | -2168.3    | -5007.1    | 382.0      | BC Section    |

**Tab.2** Direction parameter of different grounding resistances in compensation system

| Resistance/Ω | \( D_A \) | \( D_B \) | \( D_C \) | Result         |
|--------------|-----------|-----------|-----------|---------------|
| 10           | -1804.6   | -1488.7   | 282.9     | BC Section    |
| 50           | -1182.3   | -1329.0   | 196.0     | BC Section    |
| 500          | -710.6    | -843.1    | 92.5      | BC Section    |
| 2000         | -347.2    | -377.3    | 49.3      | BC Section    |
4. Conclusion

In the paper, a new method for small current grounding system single-phase-to-ground fault location using transient component and Hilbert transform is proposed. The method is implemented based on the FA system, and is not affected by the neutral point operation mode and the line structure. The use of convenient line voltage signals eliminates the need to install zero-sequence voltage transformers and other signal injection equipment, with low investment and easy implementation. Each FTU only needs its own detection data, and it has its own characteristics and does not need time to accurately synchronize; the amount of uploaded data is small, and the communication system has a small burden. Different grounding forms only affect the magnitude and duration of the transient signal, and do not affect the signal characteristics and the relationship between them. Therefore, the method can be applied to various single-phase grounding forms. For arc grounding and intermittent grounding, the transient signal is more abundant, which can increase the detection reliability. Some related technical issues, such as voltage threshold setting, transient period setting, and detection sensitivity for improving high-resistance faults, need to be further studied in combination with practice.

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