On the location of a power line fault

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Abstract. The paper proposes an algorithm to exclude the aperiodic components from short circuit currents. The computer-implemented algorithm allows locating a fault and a phase failure in 0.5 - 0.6 milliseconds. During this time interval, the magnetic cores of current transformers (CTs) do not reach saturation and processors receive undistorted information from the current transformers. Four measurements of instantaneous values of currents that are made in equal time intervals (sampling intervals) are sufficient to implement the algorithm. The exclusion of aperiodic components increases the accuracy of the fault location. The algorithm can also be used in the location of open-phase fault and in the digital relay protection based on the measurement of current and voltage.

1. Introduction
The location of fault has always been and remains a relevant task since it is aimed at improving the reliability of power supply. High-voltage power lines are the most often damaged elements of electric power systems [1-4]. Line failure is always accompanied by either an insufficient electricity supply or a decrease in the quality of power supply [5-8]. Therefore, one of the most important tasks of line repair services is to fast determine the place of the fault and organize repair and restoration work [9-12]. At present, analog relay protection systems and fault locators are being replaced everywhere with digital ones [13-18]. Digital control expands the capabilities of relay protection and control systems. It allows using the information for relay protection both locally, at the site of the facility to be protected, and remotely. For example, directional protection of generators can use the information on the voltage of other generators, transformers, and even power lines, which are situated at a distance from the generators but have electrical coupling with failed generators. Digital control allows filtering the sinusoidal components of current and voltage. It also enables calculation of power and resistance at the outlet of the relay protection measuring elements by fixing the state variables at the initial period of fault (0.2 - 0.25 milliseconds) [19]. Unlike analog protection, which is performed by electromechanical and electronic relays and receives operational information continuously, digital protection responds to discrete parameters divided by equal time intervals called sampling intervals. Therefore, it is very important to determine sinusoidal components in the discrete and often non-sinusoidal state variables.
Significant advantages of digital protection over analog one can be seen in differential protection of generators, transformers, and buses. The response time of the analog protection used is 40 - 50 ms. Developers of digital relay protection in many countries proposed using the information in areas of sufficiently accurate transformation. This made it possible to develop algorithms with a fault fixation time of 2 - 3 ms, i.e. the 3-ms interval of accurate transformation is sufficient for the digital relay protection measuring element [19,20].

2. Materials and methods
Consider the situation where the magnetic cores of current transformers are saturated in 3.0 - 4.0 ms. An algorithm excluding the aperiodic components of short circuit currents is proposed below. The short circuit current is equal to the sum of the aperiodic and sinusoidal components:

\[ i_{sc}(t) = I_m \cdot \sin(\omega \cdot t + \psi - \varphi) - I_{ma} \cdot \sin (\psi - \varphi) \cdot e^{-t/T} \] (1)

where \( i_{sc}(t) \) is an instantaneous value of short circuit current at time \( t \), \( I_m \) is the current amplitude, \( \varphi \) is an angle between current and voltage, \( I_{ma} \) is a value of the aperiodic component of short circuit current at the initial time, \( \omega \) is an angular frequency, \( \psi \) is an initial angle of short circuit current, \( T \) is time constant, \( t \) is the running time.

\[
\begin{align*}
    i_1 &= \frac{2 \cdot i(2 \cdot \Delta t) - i(3 \cdot \Delta t) - i(3 \cdot \Delta t)}{4 \cdot \sin (\omega \cdot \frac{\Delta t}{2})^2}, \\
    i_2 &= \frac{2 \cdot i(3 \cdot \Delta t) - i(2 \cdot \Delta t) - i(4 \cdot \Delta t)}{4 \cdot \sin (\omega \cdot \frac{\Delta t}{2})^2} \\
\end{align*}
\] (2)

Determine the time constant of the aperiodic component of short circuit current as:

\[ T_r = \frac{-\Delta t}{\ln \frac{i_2 - i(3 \cdot \Delta t)}{i_1 - i(2 \cdot \Delta t)}} \] (3)

Find angle \( \varphi_r \) through angular frequency and calculated time constant:

\[ \varphi_r = \arctan(tg(T_r \cdot \omega)) \] (4)

The aperiodic component will be determined as follows:

\[ i_A(t) = I_m \cdot [-\sin (\psi - \varphi)] \cdot e^{-t/T_r} \] (5)

The sinusoidal component equals:

\[ i_{sin}(t) = i_{sc}(t) - i_A(t) \] (6)

Phasors of voltage and current at time \( t \) are equal to:

\[ \hat{u}(t) = \sqrt{u(t) \cdot \sin(\omega \cdot t + \psi - \varphi)^2 + u(t) \cdot \cos(\omega \cdot t + \psi - \varphi)^2} \cdot e^{j\varphi_r} \] (7)

3. Research
To exemplify, we will consider a short circuit on generator buses (Fig.1) that have power of 120 MW, rated voltage of 10.5 kV, \( \cos \varphi = 0.85, x_a = 0.189, \) and \( x_3 = 0.23 \). Time constant for stator coil is 0.01 s. The parameters of the three-winding transformer TДЦ (TDC)-250/220 are: power is 250
MVA, rated voltage of high-voltage winding is 242 kV, that of medium-voltage winding is 37.5 kV, that of low-voltage winding is 10.5 kV, $U_{kh-m} = 11\%$, $U_{kh-l} = 24\%$, $U_{km-l} = 36\%$, $\Delta P_{kh} = 0.6$ MW, $\Delta P_{km} = 0.207$ MW, high-voltage windings are grounded. The line parameters are $L = 100$ km, $R = 0.33$ Ohm/km, $X = 0.36$ Ohm/km.

The aperiodic component amplitude is 23.7 kA. Four measurements after the short-circuit occurrence are: measurement interval is 0.625 ms: $i (\Delta t) = 0.468$ kA, $i (2\Delta t) = 1.82$ kA, $i (3\Delta t) = 3.939$ kA, $i (4\Delta t)$ = 6.702 kA. According to (1 – 5), time constant with accuracy to the 4th decimal place is $T = 0.00955$ s.

The calculated currents and power versus time are presented in Figs.1 and 2.

**Figure 1.** Short circuit current (1), calculated aperiodic component (2) and sinusoidal component (3)

**Figure 2.** Short Calculated power. The dashed line is the product of voltage and the complex conjugate of current, including the aperiodic component; the solid line is the product of voltage and the complex conjugate of current, excluding the aperiodic component (according to the proposed algorithm)

The developed algorithm makes it possible to calculate “future” operating parameters, therefore it is possible to determine the instantaneous values of sinusoidal components of currents, including the currents of positive, negative and zero sequences at any time and calculate their complex values by instantaneous values. The instantaneous values of the positive and negative-sequence currents can be calculated using phase currents without zero components [8] as follows:
\[ i_1(t) = [i_A(\omega \cdot t) + (i_B(\omega \cdot t + \frac{\pi}{2}) - i_C(\omega \cdot t + \frac{\pi}{2}))]/\sqrt{3}/2 \] (8)

\[ i_2(t) = [i_A(\omega \cdot t) - (i_B(\omega \cdot t + \frac{\pi}{2}) - i_C(\omega \cdot t + \frac{\pi}{2}))]/\sqrt{3}/2 \] (9)

The advantage of the proposed algorithm is the use of only four measurements of instantaneous short circuit currents. In this case, one calculates the instantaneous values of aperiodic and sinusoidal periodic components, the amplitude values and arguments of short circuit currents, active and reactive power in the electrical network components during at least two to three frequency periods when the attenuation of the aperiodic component is insignificant. The proposed algorithm enables us to build high-speed protection with the short circuit identification time equal to a quarter of the power grid frequency period. The presence of aperiodic components in the short circuit currents has a significant effect on the accuracy of fault location by modern equipment. For the measurements of currents during 5.0 - 8.0 ms, the error can reach 30% of the line length. The saturation of magnetic cores of current transformers does not affect the accuracy of determining the sinusoidal components of short-circuit currents by the proposed algorithm at least during 0.2 s.

The exclusion of aperiodic components from the measured instantaneous values of short circuit currents increases the accuracy of fault location on the power line. When the power line damage (for example, a fault) is detected from both sides of the line, we can use the equations for calculating voltage magnitudes on the line in the forward and reverse sequence from both sides of the line

\[ /\hat{U}_k/ = ch(y \cdot L \cdot k) \cdot \hat{U}_1 - Z_c \cdot sh(y \cdot L \cdot k) \cdot \hat{I}_1 \] (10)

\[ /\hat{U}_n/ = ch(y \cdot L \cdot n) \cdot \hat{U}_2 - Z_c \cdot sh(y \cdot L \cdot n) \cdot \hat{I}_2 \] (10a)

The advantage where /\hat{U}_k/ is the magnitude of the calculated voltage at a line point located at distance k from the line beginning, /\hat{U}_n/ is the magnitude of the calculated voltage at a line point located at distance n from the line end. The fault location will be at the point where the calculated /\hat{U}_k/ and /\hat{U}_n/ are equal.

Figure 3 illustrates equations (10) and (10a). A single-phase fault is located at a distance of 90 km from the beginning of the line 150 km long. Straight lines 1 and 2 correspond to the positive sequence voltage, lines 3 and 4 correspond to the negative sequence voltage.

![Figure 3](image-url)  

**Figure 3.** A change in the calculated voltage according to equations (9) and (9a) when the single-phase fault is located at a distance of 90 km from the beginning of the line 150 km long.

In the case of open-phase fault, the sum of positive-, negative- and zero-sequence currents is zero. Figure 4 shows the dependencies of this sum for a single-phase fault accompanied by a phase failure.
Figure 4. A change in the calculated voltage according to equations (9) and (9a) when the single-phase fault is located at a distance of 90 km from the beginning of the line 150 km long.

4. Conclusions
1. The paper presents an algorithm proposed to determine the aperiodic components of short circuit currents.
2. The algorithm employs only four measurements of the instantaneous values of short circuit currents, separated by three sampling intervals. This makes it possible to neglect the possible saturation of current transformer magnetic cores.
3. The algorithm can be used to calculate the positive-, negative- and zero-sequence currents and any of their combinations, as well as resistance and power that are used in relay protection and emergency control at any time not covered by scanning (i.e. a future period) by measuring only four values of instantaneous short circuit currents within 2.0 - 2.5 ms.
4. The algorithm improves the accuracy of power line fault location.

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