Directional protection of substation equipment

N S Buryanina¹, Y F Korolyuk¹, M L Koryakina¹, E V Lesnykh² and K V Suslov³

¹Chukotka branch of North-Eastern Federal University, 3, Studencheskaya str., Anadyr, 689000, Russia
²Siberian Transport University, 191, D. Kovalchuk str., Novosibirsk, 630049, Russia
³Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, 664704 Russia

E-mail: bns2005_56@mail.ru

Abstract. The introduction of microprocessor technology in the management of energy objects, including diagnostics, into relay protection and automation, allows combining and unifying relay protection of individual objects into a single system. One of the methods of unified relay protection may be directional protection. It is possible to develop and offer directional protection for generators, transformers, which are currently not used. An obstacle to the use of directional protection of generators and transformers is the presence of aperiodic components in the short-circuit currents, that introduce distortions in determining the angle between the short-circuit currents and voltages. At the “Power Supply” Department of the North-Eastern Federal University named after M.K. Ammosov a method that excludes aperiodic components in the secondary currents of current transformers of power system objects was developed, which made it possible to exclude incorrect actions of directional protections, including when saturating the current transformer magnetic cores. The method is based on processing four instantaneous samples of currents separated by identical sampling intervals.

1. Introduction
The local power system can be represented as the union of individual objects connected by bars, often also by power lines. Local objects can be generators, transformers, connecting them to the line. As a rule, local systems are settlements, industrial and national economic objects. Figure 1 shows an example of a local power system. The system consists of two generators, one of which operates on generator voltage buses, the second one through a transformer on high voltage buses \( U_2 \) – a line that combines the system under consideration with a combined one.

For relay protection of the external network with voltage \( U_4 \) short circuits (SC) 1 and 2 are internal. An external SC for the protection of generators and transformers is a SC at point 1. The directions of the currents relative to the voltage of this point are shown in Figure 1. The disconnection is affected by protection of the transformer, which connects the voltage buses \( U_1 \) and \( U_2 \) and the generator-transformer block. With a SC at point 2, the currents \( I_1 \), \( I_2 \) and \( I_3 \) change the direction to the opposite, the generator is turned off by protection. Line W is disconnected at SC at point 1.

2. Research objective
It is proposed to determine the direction from the place of measurement of the currents supplied to the microprocessors in the SC side by means of the parameters of the direct and reverse sequence. The instantaneous values of the currents of the direct and inverse sequences are proposed to be calculated via phase currents without zero components [1]:

\[
i_1(t) = \frac{i_A(t) + \frac{i_B(t + \frac{T_C}{4}) - i_C(t + \frac{T_C}{4})}{\sqrt{3}}}{2} \\
i_2(t) = \frac{i_A(t) - \frac{i_B(t + \frac{T_C}{4}) - i_C(t + \frac{T_C}{4})}{\sqrt{3}}}{2}
\]  

(1)

where \(i_1(t), i_2(t)\) – instantaneous values of direct and reverse sequence currents at time \(t\); \(i_A(t), i_B(t), i_C(t)\) – instantaneous values of phase currents A, B and C at time \(t\); \(T_C\) – the period of sinusoidal currents expressed in radians.

In rare cases of three-phase short-circuits near the installation sites of directional protection, it is impossible to reliably obtain information about voltages due to their magnitude. The secondary voltages supplied to the analog relay protection devices in this case are either zero or may be distorted. The introduction of digital control of the electric power industry facilities allows conducting the analysis of modes of several objects simultaneously. To implement digital directional protection in these cases, it is possible to use the voltage of other elements of the electrical system. For example, with a SC at point 1, when the voltages of all three phases of \(U_2\) are equal to zero, the voltages \(U_1, U_3\) and even \(U_4\) can be used.

This circumstance allows recommending digital directional protection as a universal for lumped objects.

3. Materials and methods

SC currents, as a rule, consist of periodic sinusoidal and aperiodic components [2]:

![Figure 1. Example of local power system](image-url)
\[ i_{\text{calc}}(t) = I \cdot \sin(\omega t + \psi - \varphi) - I \cdot \sin(\psi - \varphi) \cdot e^{-\frac{t}{T_a}} \] (2)

where \( \omega \) – angular frequency expressed in radians and equal to \( 2\pi f \); \( f \) – network frequency expressed as \( 1/s \); \( I \) – current amplitude; \( T_a = L/R \) – the constant of the network which is equal to the ratio of inductance and equivalent electromotive force of the network to the short circuit point; \( R \) – active resistance.

The unknowns in equation (2) are determined using four samples of instantaneous currents separated by the same sampling intervals \( \Delta t \). The authors proposed to calculate the instantaneous current values of currents with a significant decrease in aperiodic components using three samples:

\[ i_{\text{calc}}(n\Delta t) = \frac{2 \cdot i(n \cdot \Delta t) - i((n-1) \cdot \Delta t) - i((n+1) \cdot \Delta t)}{4 \cdot \sin^2(\omega \cdot \frac{\Delta t}{2})} \] (3)

where \( n \) – sample sequence number.

Essentially, if the current contains sinusoidal and aperiodic components, the aperiodic component in the calculated current value decreases and the sinusoidal component is reproduced without distortion. This allows selecting the aperiodic component of the current. By substituting the values of the samples into the following formula, one can calculate aperiodic components at the moment of time \( 2\Delta t \) and \( 3\Delta t \). It is possible to eliminate sinusoidal components from the short-circuit current as

\[ i_{\text{calc}}(2\Delta t) - i(3\Delta t) \quad \text{and} \quad i_{\text{calc}}(\Delta t) - i(2\Delta t) \] (4)

The time constant \( T_a \) and the current phase \( \varphi \) are defined as:

\[ T_a = -\frac{\Delta t}{\ln(i_{\text{calc}}(2\Delta t) - i(3\Delta t)) - \ln(i_{\text{calc}}(\Delta t) - i(2\Delta t))} \] (5)

\[ \varphi = \arctg(\omega \cdot T_a) \] (6)

The current amplitude is defined as:

\[ I = \frac{i(n \cdot \Delta t)}{\sin(\omega \cdot n \cdot \Delta t + \psi - \varphi) - \sin(\psi - \varphi) \cdot e^{-n\Delta t/T_a}} \] (7)

4. Research

Let us consider the example of a current equal in amplitude in relative units of 2 (two), the initial phase of the current is zero, the network time constant from the equivalent EMF to the SC point is 0.01 s., the sampling interval \( \Delta t = 0.000625 \) s., \( \varphi \) angle of the resistance of the network from the equivalent EMF to the SC point – one radian.

\[ i_{\text{esc}}(t) = 2 \cdot \sin(\omega t + \psi - \varphi) - 2 \cdot \sin(\psi - \varphi) \cdot e^{-\frac{t}{0.01}} \]

The dependence of the current on time is shown in Fig. 2.

Four samples with four-digit precision:

\[ i(\Delta t) = 0.0395, i(2\Delta t) = 0.1533, i(3\Delta t) = 0.3324, i(4\Delta t) = 0.5656. \]

Calculated current values at time points \( 2\Delta t \) in \( 3\Delta t \):

\[ i_{\text{calc}}(2\Delta t) = \frac{2 \cdot (2\Delta t) - i(\Delta t) - i(3\Delta t)}{4 \cdot \sin^2(\omega \cdot \frac{\Delta t}{2})} \quad i_{\text{calc}}(3\Delta t) = \frac{2 \cdot (3\Delta t) - i(2\Delta t) - i(4\Delta t)}{4 \cdot \sin^2(\omega \cdot \frac{\Delta t}{2})} \]

\[ i_{\text{calc}}(2\Delta t) = -1.69922, i_{\text{calc}}(3\Delta t) = -1.40777 \]

The time constant \( T_a \) and the phase current \( \varphi \)
\[ T_a = \frac{-\Delta t}{\ln \left( \frac{i_{\text{calc}}(2\Delta t) - i(3\Delta t)}{i_{\text{calc}}(\Delta t) - i(2\Delta t)} \right)} = 0.00999 \, \text{c.} \]

\[ \varphi = \arctan(T_a \cdot \omega) = 1.264 \, \text{rad} \]

The amplitude of the current is:

\[ I = \frac{0.395}{\sin(\omega \cdot 0.000625 - 1.2624) - \sin(-1.2624) \cdot e^{-0.00625/0.00999}} = 1.9998 \, \text{r. u.} \]

Figure 2. Example of the change in SC current over time.

Errors in the calculation of values that determine the currents are not more than 0.1%.

The change of the aperiodic component in time is described by the equation:

\[ i_A(t) = -I \cdot \sin(\psi - \varphi) \cdot e^{-t/T_a} \quad (8) \]

The sinusoidal component is defined as:

\[ i_{\text{sin}}(t) = i(t) - i_A(t) \quad (9) \]

Figure 3. Changes in SC current over time (curve 1), aperiodic component calculated according to (8) (curve 2), sinusoidal component calculated according to (9) (curve 3).
The change in currents over time (1 is the total SC current, 2 is the aperiodic component of the current, 3 is the sinusoidal component of the current) is shown in Fig. 3.

Equations (1) involve the calculation of the currents of B and C phases at intervals of time that are separated from the time of measuring the current of A phase by a quarter of the period. I.e., the processing time of the currents is – 5 ms. By this time, the magnetic circuits of current transformers in some cases may become saturated, and the results of the calculation will be incorrect.

An idealized picture of the saturation of the magnetic circuits of current transformers is shown in Figure 4. For half the period, the secondary current in time has two sections: an ideal transformation and a section with an error where part of the secondary current is missing. If the secondary current is decomposed into a Fourier series, then the first harmonic has a frequency greater than the nominal one and is smaller in magnitude than the secondary current reduced to the primary one.

![Diagram](image)

**Figure 4.** Primary and secondary currents at saturation of magnetic circuits of current transformers.

The method of four samples has three advantages that distinguish it from all currently used ones in digital control:

- uses information about short-circuits in a very short period of time (up to 2.0–2.5 ms), which does not allow tuning away from the saturation of the magnetic conductors of current transformers;
- completely excludes aperiodic components from secondary currents entering the measuring bodies of digital relay protection and automation;
- determines the sinusoidal components of currents on time intervals outside the measurement interval (after 2.0–2.5 ms).

The third advantage is especially valuable when calculating secondary parameters, such as direct and inverse sequence currents, powers, resistances, etc. Four samples are sufficient to implement any protections that respond to the periodic components of the mode parameters. Figure 5 shows the time dependences of the active and reactive powers calculated as the product of the voltage complex and the conjugate current complex. Dependences 5 and 7 – the current is calculated according to (3), dependences 6 and 8 – the current is calculated according to (3–9). According to the work (3), power calculation errors reach 25–100 % over the time interval 0–0.01 s. When calculating the currents according to the works (3–9), the errors in calculating the powers are zero.

Sampling intervals of 0.5 and 0.625 milliseconds can be obtained as part of a sampling interval equal to a quarter of the current network frequency period. In its turn, the sampling interval in a quarter of the period of the network frequency is obtained by fixing zero-voltage transitions on the active and inductive resistances of the RC – link, as shown in Figure 6 [3].
Figure 5. Active and reactive powers in different calculation methods of SC currents.

Figure 6. Ensuring sampling intervals equal to a quarter of the period of the network frequency.

The sampling interval equal to a quarter of the period of the network frequency can be used in the development of emergency control algorithms [4].

5. Conclusions
1. The method which makes it possible to isolate the periodic components of short-circuit currents from currents equal to the sum of the periodic and aperiodic components has been developed.
2. The algorithm that implements the method uses a total of four samples, separated by three sampling intervals, which makes it possible not to take into account the possibility of saturation of the magnetic circuits of current transformers, removing information in areas of sufficiently accurate transformation.
3. The method allows calculating the currents of the direct, inverse sequences, and any combinations thereof, resistance, power, used in the relay protection and emergency control automation at any moment of time.
4. Directional protection is proposed for generators and transformers. In order to exclude "dead" zones with close three-phase short circuits, it is proposed to use voltages of adjacent elements of the electrical network that are connected to the protected objects.

5. Transferring the method to reading information for the operation of automation allows increasing the sampling interval to a quarter of the period of industrial frequency.

6. Acknowledgments
The study was carried out with the financial support of the Russian Foundation for Basic Research and the Subject of the Russian Federation – the Republic of Sakha (Yakutia) № 18-48-140 010.

References
[1] Buryanina N S, Korolyuk Y F and Lesnykh E V A 2016 Method for determining the instantaneous values of the parameters (currents and voltages) of the forward and reverse sequences Pat. no EN, 265 63 49, MPK H02J 13/00 (2016/01) no 2016137597; Appl. 20.09.2016, publ. 05.06.2018, Bul. no 16
[2] Stroev V A 1996 Transients of electrical systems in examples of illustrations (Moscow: Znak Publ) 223 p
[3] Buryanina N S, Korolyuk Y F and Lesnykh E V 2016 Method of reference of instantaneous values of voltages Pat. 2 625 172, RU, IPC H02J 13/00 (2006.01) Russian Federation, no 2016105446; Appl.17.02.2016; publ. 12.07.2017, Bul. no 20
[4] Greshnov E B and Korolyuk Y F 1982 About the choice of the sampling interval of the analog parameters entered into the computer for programmable protections Electronic Simulation 5 71–74 (Kiev)