Elimination of aperiodic components of measuring elements of relay protection

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

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

E-mail: bns2005_56@mail.ru

Abstract. The authors propose the algorithms to calculate the actual values of currents and their derivatives. The algorithms allow a sharp reduction in the aperiodic components of currents in the calculated actual values and their derivatives. The algorithms are developed to calculate the instantaneous values of positive- and negative-sequence currents when the information obtained during a time interval equal to two milliseconds or less is used. An algorithm is devised to calculate the sinusoidal components of the currents in the presence of aperiodic components in the samples. To eliminate the disoperation of digital relay protection and improve the accuracy of fault location, it is necessary to eliminate the influence of aperiodic components in the currents drawn to the measuring devices of relay protection. The algorithm completely eliminates the aperiodic component at any time constants and is implemented by four samples of currents. The four samples of currents separated by three sampling intervals are sufficient for calculating all the parameters of currents, including the positive and negative-sequence currents, in particular in the case when the magnetic cores of current transformers reach saturation. The proposed methods for setting the industrial frequency parameters to avoid the aperiodic components in short-circuit currents are based on the algorithms that process the data from three and four samples of currents.

1. Introduction

The adoption of microprocessors in the control of energy systems enables these functions to be performed during transient processes as well. On the one hand, digital control during transient processes expands the possibilities of automated devices, on the other hand, it requires settings to enable relay protection to cope with interferences arising during short circuits caused by the non-utility frequency conditions. This mainly involves the algorithms of protections performed by electromechanical relays [1 - 5]. The difference between the digital relay protection and analogue one is that the analogue protections receive the data on operating conditions continuously, whereas digital relay protections receive the data discretely at equal time intervals called sampling intervals.

Particular attention is paid to the protection that employs the data on changes in currents [6-8]. Let us consider the application of the principles of analogue protections to digital ones. It takes the overcurrent protection at least the time equal to the period of utility frequency to respond to the integral value of the current. The overcurrent protection performed by microprocessors that respond to
the integral values of currents does not reduce the time of relay operation, i.e. there are no important advantages of microprocessors over analogue devices in this case.

The significant advantages of digital protection over analogue protection manifest themselves in the differential protection of generators, transformers, and buses. The response time of the applied analogue protection on the basis of relay with fast satiable transformers and with voltage-restrained overcurrent relay [9] is 40 - 50 ms.

The developers of digital relays [11–14] abandoned the principles laid down in the above relay. It was proposed to use information in the areas of sufficiently accurate transformation, which made it possible to develop algorithms with a fault fixing time of 2–3 ms. These algorithms however faced the phenomenon of saturation of the magnetic core of current transformers [15].

The main studies in the field of digital protection are summarized in [15-18], where the authors consider the differences between analogue and digital protections, the advantages of the latter in hardware reliability, the expansion and improvement in the quality of protective functions, totally new protection control capabilities, etc. However, the issue of tuning the protections to cope with the interferences caused by the non-utility frequency parameters is not fully resolved. There is also still no solution to the problem of locating damage on power lines in the presence of interference from aperiodic and high-frequency components [19–22].

2. Research objective

In order to eliminate false operation of digital relay and to more accurately locate short circuits, it is required to eliminate the influence of aperiodic components in the currents supplied to the measuring devices of the relay. Below, we propose the algorithms that reduce aperiodic components dozens of times in the case of three samples of currents during short circuit, and completely eliminate them when the data from four samples are used [24,25].

3. Materials and methods

In the case of three samples from the instantaneous values of current separated by equal sampling intervals, we obtain an actual value of the current at the time of the average sample, and its derivative:

\[ i_{ev}(t) = \frac{2 \cdot i(t) - i[t + \Delta t] - i[t - \Delta t]}{4 \cdot \sin^2 \left( \frac{\omega \cdot \Delta t}{2} \right)} \]

\[ i'_{ev}(t) = \frac{i[t + \Delta t] - i[t - \Delta t]}{2 \cdot \sin(\omega \cdot \Delta t)} \]

where \( t \) is the current time; \( \Delta t \) is the sampling interval separating the sample; \( \omega \) is the angular frequency; \( t \) is the instantaneous value of the primary current to be measured; \( i_{ev} \) – calculated secondary current.

It is easy to see that \( i_{ev}(t + \Delta t) \) exactly repeats the function \( i(t) = \sin(\omega \cdot t + \Delta t) \), if one uses the equation \( \sin(\omega \cdot t + \pm \omega \cdot \Delta t) = \sin(\omega \cdot t) \cdot \cos(\omega \cdot \Delta t) \pm \cos(\omega \cdot t) \cdot \sin(\omega \cdot \Delta t) \).

i.e. equations (1) accurately calculate sinusoidal components and filter aperiodic components. Figure 1 demonstrates the aperiodic components of currents and their derivatives calculated with (1) for different time constants of the protected part of the electrical network, if the primary current at time \( t = 0 \) is specified by the aperiodic component equal to one.

The reduction in aperiodic components in the actual values of currents is due to the subtraction of two close instantaneous values of the current, spaced in different directions from the time \( t \). Moreover, the greater is the time constant \( T \) of the electrical network part from the equivalent EMF to the short-circuit point, the smaller is the residual part of the aperiodic component after solving equation (1). In the algorithms considered in [17] however the aperiodic component is determined as a half-sum of two close values, i.e. it is practically not taken into account.
4. Research

At time $t = 0$, the secondary current at a time constant of the protected network area of $0.005$ s is equal to $35\%$ of the primary current, and the derivative is $53\%$. With time constants up to $0.01$ s, the saturation of the magnetic cores, as a rule, does not occur. Therefore, one can begin sampling after a period of utility frequency. The residual aperiodic component in the secondary currents will not exceed $1\%$, which is sufficient for the proper operation of the relay protection. To locate the fault on the power line, the current sampling can also be started in a period from the time of the fault occurrence. For large time constants (more than $0.05$ s.), the residual aperiodic component in the secondary currents does not exceed $0.5\%$.

![Figure 1. Secondary currents and their derivatives with aperiodic primary with different time constants of the protected area network (1 – time constant $T = 0.005$ sec., 2 – $T = 0.05$ sec., 3 – $T = 0.1$ sec. For the curve 1 in Figure 1a – vertical scale in percent, for curves 2 and 3 scale in tenths of percent).](image)

In order to reduce the error caused by the presence of aperiodic components when determining the parameters of the fundamental frequency, it is proposed to once again determine the actual values of the parameters with equations (1) but use the calculated parameters as the primary ones. Figure 2 shows the obtained derivatives of the currents after the second calculation of the derivatives of the currents. After a period of network frequency, the residual aperiodic components do not exceed $0.4\%$ for any time constants of the protected network section. At the time constants greater than $0.01$ s, the error due to aperiodic components does not exceed hundredths of a percent. The minimum number of measured primary parameters with repeated use of equations (1) is five, separated by four sampling intervals. With a sampling frequency of $1600$ Hz, the four sampling intervals will be $2.5$ ms in total. During this time, as practice shows, the magnetic cores of current transformers do not reach saturation. The error in the calculation due to aperiodic components in the section of ideal transformation is $0.03\%$. The fault location algorithms on the $400$-km-long line will locate the short circuit with the accuracy of $120$ m. This allows recommending equations (1) to filter the calculated currents for all the tasks necessary to control the emergency conditions of power systems.

Consider how to determine the positive- and negative-sequence currents and voltages through the instantaneous values of the parameters. At time $t$, the phasor of the current is obtained as follows:

$$I(t) = i_n(t) + i'_n(t) \cdot j$$  \hspace{1cm} (2)

In literature (in Russia and other countries) it is proposed to determine the positive- and negative-sequence currents with a special phase A through the phasors:
The amplitude and phase of currents are defined as:

\[
I_{1a}(t) = \frac{i'_{Aa}(t) + i'_{Bb}(t) \cdot e^{\frac{j2\pi}{3}} + i'_{Ca}(t) \cdot e^{-\frac{j2\pi}{3}}}{3} \quad (3)
\]

\[
I_{2a}(t) = i'_{Aa}(t) + i'_{Bb}(t) \cdot e^{-\frac{j2\pi}{3}} + i'_{Ca}(t) \cdot e^{\frac{j2\pi}{3}} \quad \frac{3}{3}
\]

The disadvantage of calculating the positive and negative-sequence currents through phasors is a large error if the short-circuit currents contain considerable aperiodic components.

We propose calculating the instantaneous values of positive- and negative-sequence currents using two formulas:

\[
i_{1b} = \frac{i_{Aa}(t) + i_{Bb} \left( t + \frac{T_c}{3} \right) + i_{Cc}(t - \frac{T_c}{3})}{3} \quad (4)
\]

or via phase currents without zero components:

\[
i_{1b} = \frac{i_{Aa}(t) + i_{Bb} \left( t + \frac{T_c}{3} \right) - i_{Cc}(t - \frac{T_c}{3})}{\sqrt{3}} \quad (5)
\]
\[ i_2(t) = \frac{i_{AB}(t) - i_{BB} \left( t + \frac{T_c}{4} \right) - i_{CB} \left( t + \frac{T_c}{4} \right)}{\sqrt{3}} \]

where \( T_c \) - the period of the frequency voltage.

The equations (4) and (5) suggest the calculation of phases B and C in time intervals that are distant from the time of phase A current measurement by a third of the period before and after the measurement when we use (4), and by a quarter of the period – when we use (5), i.e. the processing time of the currents in the first case is 10.33 ms, in the second - 5 ms. By this time, the magnetic cores of current transformers in some cases may reach saturation, and the calculation results will prove incorrect.

The idealized picture of the saturation of the magnetic core of current transformers is shown in Figure 3. The secondary current over time has two sections in half the period: a section of an ideal transformation and a section with an error where part of the secondary current is missing. If the secondary current is expanded into a Fourier series, the first harmonic has a frequency greater than the nominal one and is smaller in magnitude than the primary current reduced to the secondary one.

Consider the effect produced by the non-utility frequency components in currents on the accuracy of determining an emergency situation during short circuits. The short circuit current in time is determined by the equation:

\[ i(t) = \frac{E_{eq} \cdot (\sin(\omega \cdot t + \psi - \varphi) - \sin(\psi - \varphi) \cdot e^{-\frac{t}{T_c}})}{\sqrt{R_{eq}^2 + X_{eq}^2}} \]

where \( E_{eq} \) – equivalent EMF; \( R_{eq}, X_{eq} \) – equivalent active and reactive resistances from the equivalent EMF to the short-circuit point; \( \omega \) – angular frequency equal to \( 2\pi f \); \( f \) – frequency; \( T_c \) – network constant equal to \( L/R \); \( \psi \) – voltage angle at which the short circuit occurred, expressed in radians; \( \varphi \) – impedance angle of a short-circuit branch.

Let us calculate the actual values of current at time instants \( \Delta t \) and \( 2\Delta t \) by the formula:

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

where \( n \) is the sequence number of the sample.

The network constant is defined as:

\[ T_c = \frac{-\Delta t}{\ln(i_{ev}(2\Delta t) - i(3\Delta t) - i(\Delta t))} \]

The angle \( \varphi \) is determined by a constant network and the angular frequency:

\[ \varphi = \arct g(T_c \cdot \omega) \]

The aperiodic component is calculated as:

\[ i_A(t) = k \cdot (-\sin(\psi - \varphi) \cdot e^{-\frac{t}{T_c}}) \]

where \( k \) is calculated as

\[ \frac{E_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} = k = \frac{i(\Delta t)}{\sin(\omega \cdot t + \psi - \varphi) - \sin(\psi - \varphi) \cdot e^{-\frac{\Delta t}{T_c}}} \]
In the event that there is a threat of the current transformer magnetic core saturation, it is proposed to create calculated currents of utility frequency for several periods ahead and ignore the saturation of the magnetic cores of the current transformer.

The algorithm for this task is as follows [23-26]:
1. Make four samples of currents and calculate the actual values of currents using equation (7) at time point’s ∆t and 2∆t.
2. Determine time constant of the network from equivalent EMF to the fault point using equation (8).
3. Determine the amplitudes and phases of the currents according to (11). The amplitudes of the currents can also be determined by the ratios of the calculated values of the sinusoidal currents to the sines of the angles of the calculated currents.
4. Determine the current values of the sinusoidal components and their derivatives at any time:

The sinusoidal component of the current is equal to:

\[ i_{\sin}(t) = i(t) - k \cdot i_d(t) \]  

(12)

\[ i'_{\sin}(t) = k \cdot \cos(\omega \cdot t + \psi - \varphi) \]  

(13)

where k – the time of calculating the actual value of currents and their derivatives.

The equations (13) and (14) can be used to determine the actual values of sinusoidal components of the currents and their derivatives at any point in time, including the points in time when the current transformer magnetic cores reach saturation. In addition, these equations allow determining the parameters of secondary currents in the “future” time. This is also relevant for the development of emergency control actions.

Thus, an algorithm has been proposed to identify the sinusoidal components of the currents for four samples separated by three sampling intervals. These samples should be stored so as not to overload computer with extra calculations, and after the line is cut, perform calculations. The complete elimination of aperiodic components from the short-circuit current equal to the sum of aperiodic and periodic components is proposed for the first time.

Based on equations (8–12), the following algorithm for calculating the fundamental frequency component of current can be also recommended for the protections using the information on currents:

- Make four samples of currents;
- Calculate actual values of currents using equation (8) at time points t = ∆t and t = 2∆t;
- Determine the time constant of the electrical network from the short circuit to the generators using equation (9);
- Determine the impedance angle from the equivalent EMF to the short-circuit point;
- Determine aperiodic component of the current using equation (11);
• Determine the component of the current of fundamental frequency (12);
• Determine the parameters of currents using equations (4-8) for the digital current protection. The approximate execution time of the algorithm for the currents of three phases will not exceed the time equal to half the period of the utility frequency.

In order to eliminate the influence of a frequency change, namely, a constant sampling interval, on the error in calculating the actual value of network operating parameters, the sampling interval should be calculated as part of the voltage zero crossing intervals on the resistance and capacitance of the RC circuit [21]. These crossings always correspond to a quarter of the frequency period. If the network frequency is not equal to the nominal one and the sampling rate is equal to 1600 Hz, the sampling interval will be equal to 1/32 of the voltage zero crossing interval of the RC circuit.

5. Conclusions
The algorithm is proposed to calculate the actual values of secondary currents and their derivatives that dramatically reduce the magnitude of aperiodic components. Thus, only periodic components are brought to the relay protection. The algorithm is based on a sample for calculating three values separated by identical sampling intervals, and provides an aperiodic component with a residual aperiodic component at the time of the average measurement. The residual aperiodic components do not exceed units of percent of those present in the measured secondary currents. Moreover, the greater is the time constant of the electrical network section from the short circuit to generators, the lower is the residual in the calculated secondary currents.

The algorithm is proposed to completely eliminate the aperiodic components in secondary currents using only four samples. The application of the algorithm eliminates the influence of the saturation of the magnetic core of current transformers on the operation of the relay protection. The algorithm is proposed for the first time.

The algorithm is proposed to determine the actual values of currents and their derivatives at "future" points in time, including the saturation of the magnetic cores of current transformers. This allows the use of the information received during 0.02 s. from the time of fault occurrence.

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] Bayliss C R and Hardy B J 2012 Chapter 10: Relay Protection Transmission and Distribution Electrical Engineering (Fourth Edition) pp 287-359
[2] IEC 2006 Electromechanical elementary relays – Part 7: Test and measurements procedures, IEC 61810-7
[3] Gurevich V 2006 Electric Relays: Principles and Applications (first ed.), (CRC Press, Boca Raton)
[4] Akke M and Thorp J 1998 Some improvements in the three-phase differential equation algorithm for fast transmission line protection IEEE Transl. Power Delivery 13(1) 66–72
[5] Gergić B and Hercog D 2019 Design and implementation of a measurement system for high-speed testing of electromechanical relays Measurement 135 112-121
[6] Saleh K A, Zeineldin H, Al-Hinai A and El-Saadany E F 2015 Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic IEEE Transl. Power Delivery 30 (2) 537-544
[7] Suslov K, Gerasimov D and Solodusha S 2015 Smart grid: Algorithms for control of active-adaptive network components, IEEE Eindhoven PowerTech (Netherlands)
[8] Enriquez A C and Martinez E V 2006 Enhanced time overcurrent coordination Electric Power Systems Research 76 457-465
[9] Drozdov A D 1965 Electrical curciuts with ferromagnetic cores in relay protection (Energiya)
[10] Gers J and Holmes E 1998 Protection of Electricity Distribution Networks The Institution of Electrical Engineers
[11] Haeg H and Forster M 1965 Elektronischer Sammelschienenschutz Brown Boveri Mitteilungen 53 326-339
[12] Evans E J and Wells G 1970 Use of Sampling to Detect Transient Saturation in Protective Current Transformers IEEE Transl. on Instrumentation and Measurement 19(3) 144-147
[13] Kuzhekov S L and Nudel’man G S 2009 Maintaining the right function of microprocessor devices of differential protection in case of current transformers saturation Izvestiya Vuzov Elektromekhanika 4 12-19
[14] Gangadharan P K, Sidhu T S and Finlayson G J 2007 Current transformer dimensioning for numerical protection relays IEEE Transl. on Power Delivery 22 (1) 108–115
[15] Zinov’ev D V 2009 Development of the processor information analysis theory in electrical system and its application to relay protection Cheboksary
[16] Hosemann G, Steigerwald H 1993 Modal saturation detector for digital differential protection IEEE Transl. on Power Delivery 8 (3) 933–940
[17] Macieira G L and Coelho A L 2017 Evaluation of numerical time overcurrent relay performance for current transformer saturation compensation methods Electric Power Systems Research 149 55-64
[18] Shneerson E V 2007 Digital relay protection (Energoatomizdat)
[19] Kılıçkiran H C, Şengör İ, Akdemir H, Kekeçoğlu B and Paterakis N G 2018 Power system protection with digital overcurrent relays: A review of non-standard characteristics Electric Power Systems Research 164 89-102
[20] Arzhannikov E A, Lukoyanov V Y and Misrikhaniv M Sh 2003 Identification of short circuit place on high voltage lines (Energoatomizdat)
[21] Kulikov A L and Obalin M D 2015 Software development to support of solution in damage elimination on transmission lines Izvestiya Vuzov “Elektromekhanika” 2 70-75
[22] Kulikov A L 2017 Algoritm of the damage identification of transmission lines with branches Vestnik NGIEI 9(76) 29-38
[23] Buryanina N, Korolyuk Y, Koryakina M, Lesnykh E, Suslov K and Shamarova N 2019 Using a new algorithm of current protection for substations Proceedings of the 10th International Scientific Symposium on Electrical Power Engineering, ELEKTROENERGETIKA
[24] Buryanina N S, Korolyuk Y F and Lesnykh E V 2016 RU, Patent No. 2 625 172 The way to count voltage and current instantaneous values
[25] Kondrat’ev V V, Govorkov A S, Lavrent’eva M V, Sysoev I A and Karлина A I 2016 Description of the heat exchanger unit construction, created in IRNITU International Journal of Applied Engineering Research 11 (19) 9979-9983
[26] Sysoev I A, Kondrat’ev, V V, Zimina T I and Karлина A I 2018 Simulation of the Energy States of Electrolyzers with Roasted Anodes at Elevated Currents Metallurgist 61(11-12) 943-949