DOI 10.1007/s10749-015-0577-3
Power Technology and Engineering *Vol. 49, No. 1, May, 2015*

AN ANALYSIS AND INVESTIGATION OF METHODS OF BRAKING DIGITAL DIFFERENTIAL PROTECTIONS OF BLOCK TRANSFORMERS

A. M. Dmitrenko[1] and D. P. Zhuravlev[2]

Translated from *Élektricheskie Stantsii*, No. 11, November, 2014, pp. 36 – 41.

Modern methods of braking digital differential protections of block transformers when there are external short circuits are considered. The effect on the braked quantities of such factors as the phase difference between the side currents, and also saturation of the current transformers is described.

Keywords: block transformer; differential protection; braking; saturation of the current transformer core; limit multiplicity of the current transformer accuracy.

When choosing methods of braking differential protections of the block transformers of electric power plants, it is necessary to take the following main factors into account:

— the comparatively large values of the currents when there is a short circuit at the sealing off to the supply transformer due to its closeness to the generator;

— the considerable number of sides of the differential protection (which can be as high as five).

In view of the above, only those braking methods are considered which are invariant to the external short-circuit current, irrespective of the number of controlled sides. These methods include the following:

— braking from the half-sum of the moduli of the secondary currents of all sides [1]

$$I_b = 0.5(I_{12} + I_{22} + ... + I_{n2}); \tag{1}$$

braking from the maximum of the moduli of the currents of all phases and all sides[3]

$$I_b = \max\{I_{12}, I_{22}, ..., I_{n2}\}, \tag{2}$$

where I_{12}, I_{22}, ..., I_{n2} are the effective values of the first (fundamental) harmonics of the secondary currents of the sides, after corresponding scaling and after taking into account the connection group of the power transformer.

The use of the coefficient 0.5 in formula (1), compared with the method used in [2], has the following advantages:

— when the short-circuit currents of the supply sides have the same phase, the braked current is equal to the reduced current of the external short circuit, which enables the procedure for calculating the settings of the braking coefficient k_b to be simplified and makes it more transparent;

— when using the braking characteristic with a horizontal part in the initial section (Fig. 1), the current at the start of braking $I_{b.s.1*}$ easily agrees with the nominal current of the protected transformer. For example, when $I_{b.s.1*} = 1$ the braking begins at the nominal load current of the transformer.

When constructing the braking characteristics, one takes as the basis currents the nominal currents of the protection device (in general they may be different for different sides of the protection).

The braking coefficient is calculated from the formula: $k_b = \tan\alpha$.

In the United Power System of Russia, the transformer testing procedure is important. Testing is usually carried out by applying a voltage from the higher-voltage side. It is then desirable to increase the sensitivity of the differential protection for damage currents, not exceeding the setting of the differential cut-off. When using formula (*1*) and the braking characteristic shown in Fig. 1, the currents at the start of braking $I_{b.s.1*}$ and $I_{b.s.2*}$ are doubled (the braking characteristic for this case is shown by the dashed curves). The sensitivity coefficient is then increased, since the ratio of the damage current to the operating current on the braking characteristic increases. When using formula (*2*), the sensitivity in the testing mode remains unchanged, which imposes certain limitations on the maximum possible values of the braking coefficients k_{b1} and k_{b2}.

When transmitting high powers over long distances, superhigh-voltage lines are used. 500 kV power lines have the greatest overall length in Russia, and these were taken as a typical object for investigation. Long power lines are usually sectioned for the purpose of ensuring both stability and

[1] Chuvash State University, Cheboksary, Russia.
[2] SPE "EKRA" LLC, Cheboksary, Russia; e-mail: zhuravlev_dp@ekra.ru
[3] Based on the sections on the protection of transformers in the Technical Handbook RET 521 published by ABB and the General Electric Guide on the use of the T60.

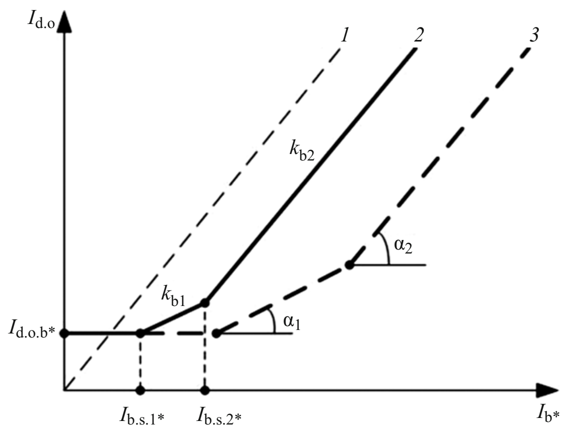

Fig 1. The current characteristics in the relay when there is a short circuit in the zone (*1*), braked under normal conditions (*2*) and in the transformer testing mode (*3*): $I_{d.o*}$ is the operating current of the differential protection, and $I_{d.o.s*}$ is the operating current of the differential protection at the start of the braking characteristic (when $I_{b*} = 0$).

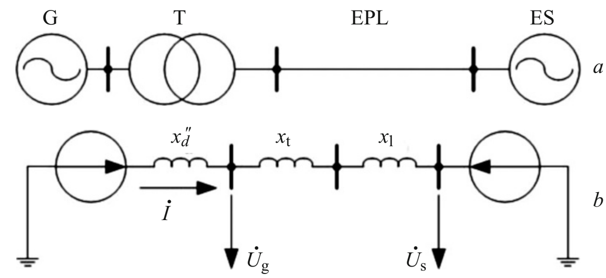

Fig. 2. Circuit of the network (*a*) and its theoretical equivalent circuit (*b*): x''_d is the supertransfer reactance, x_t is the transformer reactance, x_l is the line reactance, $\dot{U}_g$ is the generator voltage and $\dot{U}_s$ is the system voltage.

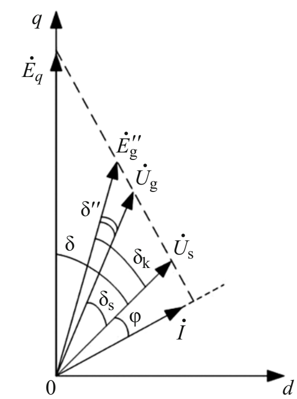

Fig. 3. Vector diagram of the currents, voltages and EMF of a nonsalient synchronous machine.

the required voltage mode of operation over the whole length of the line. To achieve this, shunting reactors are connected at intermediate substations and power takeoff of the active power is carried out.

The longest permissible length of a section of the power line is 500 km [3], but in practice it does not usually exceed 400 km.

Shunting reactors are also set up at the electric stations, and hence, when calculating the power transmitted along the power line, one need not take into account the transverse capacitances in the Ð-shaped equivalent circuit of the line (Fig. 2).

When there is a short circuit at the sealing off to the transformer, free currents with a frequency different from the nominal value will appear from the side of the block transformer. The occurrence of these currents is due to the presence of the considerable distributed capacitance of the line. Since, when calculating the currents of the sides, frequency filtering is used for the purpose of separating the fundamental harmonic, the presence of free (attenuating) currents is of no importance.

It should be noted that the values of the line reactance x_l, calculated from the formula $x_l = x_s l$ (where x_s is the reference value of the specific reactance and l is the line length), and the values of x_l, obtained from the wave parameters of the line, will differ somewhat. However, for an electric power line length not greater than 400 km this difference can be neglected.

In Fig. 3 we show a vector diagram of the currents, voltages and EMFs of a nonsalient pole synchronous machine, connected to a system of infinite power.

The active power P, transmitted along the electric power line (EPL), is usually expressed in terms of the EMF at the transverse axis E_q [4]:

$$P = \frac{E_q U_s \sin\delta}{x_d + x_b + x_l},$$

where x_d is the reactance of the machine.

The use of this expression is due to the fact that the angle δ represents the position of the machine rotor in space, and this is convenient for investigating electromechanical transients.

When calculating the short-circuit currents, it is convenient to take as the basis quantities the complex (vector) of the generator voltage $Udoe_g$, which enables us to calculate the supertransfer EMF of the generator from the formula

$$\dot{E}''_{g.p} = \dot{U}_{g.p} + jx''_d \dot{I}_1,$$

where $\dot{E}''_{g.p}$ and $\dot{U}_{g.p}$ are phase quantities, x''_d is the supertransfer reactance and $\dot{I}_1$ is the current of the previous load regime.

As can be seen from Fig. 3, the complex leads the complex $\dot{E}''_g$ by an angle δ″. The angle δ″ has its greatest value when the generator only delivers active power (φ = 0°).

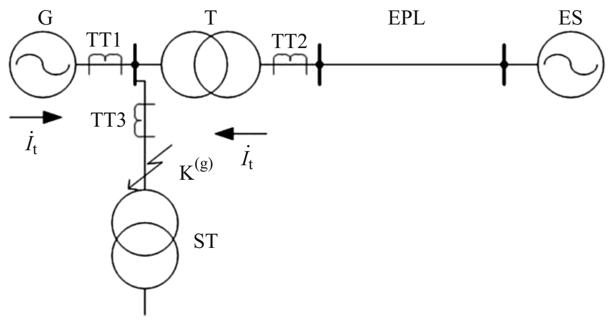

Fig. 4. Circuit of the network with a three-phase short circuit in the supply transformer (ST) circuit.

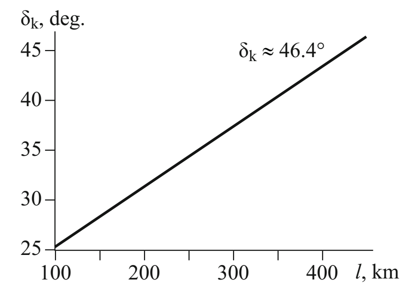

Fig. 5. Graph of the phase difference between the side currents for a short circuit as a function of the length of the electric power line.

Then, under nominal operating conditions of the generator ($I_l = I_{g.nom}$, $U_g = U_{g.nom}$) we obtain

$$\tan \delta'' = x''_{d*}. \quad (3)$$

For example, for the TVV-1000-4 generator we have $x''_{d*} = 0.32$. Taking formula (3) into account we obtain that $\delta'' = 18°$.

To find the angle δ_s we will use the following expression for the power transmitted along the transmission line [4]

$$P = \frac{U_g U_s}{x_b + x_l} \sin \delta_s.$$

From this we obtain

$$\delta_s = \arcsin \frac{P_g (x_b + x_l)}{U_g U_s}. \quad (4)$$

In formula (4) the reactance x_t and x_l, and also the voltage U_s are more conveniently reduced to the generator voltage. As can be seen from Fig. 3, the required angle

$$\delta_k = \delta'' + \delta_s.$$

It is well known that in branches to the normal supply transformer (ST) (Fig. 4), the short-circuit currents can reach 200 kA ore more.

In this case, for a 500 kV electric power line up to 450 km long with a generator power $P_g = 1000$ MW, it has been established that the value of the angle δ_k between the combinations of the short-circuit currents of the generator $\dot{I}_g$ and the transformer $\dot{I}_t$ may reach 46.4° (Fig. 5).

It should be noted that, for the maximum possible currents of an external short circuit, the total error of the current transformers (CT) should not exceed 10%. As was mentioned previously, the short-circuit current at the sealing off to the supply transformer may reach 200 kA or more. The primary nominal current of CT3, connected at the sealing-off point, usually does not exceed 3 kA. Correspondingly, the relative short-circuit current is

$$I_{sc*} = \frac{I_{sc}}{I_{1\,nom.CT}} = \frac{200}{3} = 66.7,$$

where I_{sc} is the short-circuit current, I_{sc*} is the relative short-circuit current and $I_{1nom.CT}$ is the primary nominal current of CT3.

We can assume that there is no saturation of the current transformer under steady conditions if the following condition is satisfied:

$$K_l \geq I_{sc*}, \quad (5)$$

where K_l is the limit accuracy multiplicity of the current transformer (K_5 and K_{10}).

It is not always possible to satisfy condition (5) since the current transformers employed usually have a nominal limit multiplicity $K_l = 20 - 30$, while the length of the connecting wires between the current transformer and the protection cabinet is quite considerable (which does not enable the load of the current transformer to be reduced substantially compared with the nominal value). The use of a current transformer with a secondary nominal current of 1 A is also not always possible.

Saturation of the magnetic conductor of the current transformer was taken into account by using the simplest piecewise-linear approximation of the relation $B = f(H)$, where B is the magnetic induction and H is the magnetic field strength. We assumed the so-called linearized magnetization characteristic, consisting, in the first quadrant, of two sections of straight lines: a vertical straight line for $H = 0$ and an inclined line for $H > 0$.

The form of the curve of the secondary current i_2, after the core of the current transformer is saturated, was investigated in general form in [5]. For a practically resistive load on the current transformer and $T_{2s} \leq 1$ msec, the expression

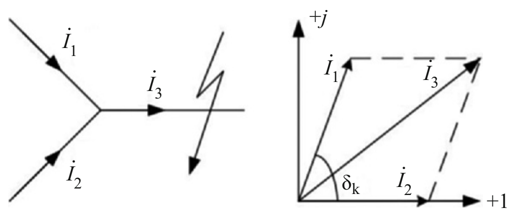

Fig. 6. Relation between the side currents for an external short circuit in the circuit with the need for braking from three sides.

for the current i_2 under steady conditions can be written in the following form:

$$i_2 = A_2 e^{-(t-t_s)/T_{2s}} + \omega T_{2s} I'_{1m} \sin\left(\omega t + \arctan\frac{1}{\omega T_{2s}}\right), \quad (6)$$

where A_2 is the initial value of the exponential component, T_{2s} is the attenuation time constant of the exponential component when the core of the current transformer is saturated, $t_s \le t \le t_B$, ts is the time until the core of the current transformer becomes saturated, t_B is the instant when the core of the current transformer emerges from saturation and I'_{1m} is the reduced amplitude of the primary current of the current transformer.

The time constant of the secondary circuit of the current transformer can be calculated in general form from the formula

$$T_2 = \frac{L_0}{r_{w.2} + r_1}, \quad (7)$$

where L_0 is the inductance of the magnetization branch of the current transformer, $r_{w.2}$ is the dc resistance of the secondary winding of the current transformer and r_1 is the resistance of the transformer load.

In the case considered, we must substitute L_{0s} (the inductance under saturation conditions) into formula (7).

Assuming that $t = t_s$, we obtain the following equation from (6):

$$i_2 = i'_1 = A_2 + \omega T_{2s} I'_{1m} \sin\left(\omega t_s + \arctan\frac{1}{\omega T_{2s}}\right),$$

from which we can find the initial value of the exponential component A_2.

In this paper we have considered the processes occurring in a current transformer when the value of the magnetic field strength is a maximum, $H = 100{,}000$ A/m. Then L_{0s} can be calculated from the approximate formula [5]

$$L_{0s} \approx \frac{\mu_0 w_2^2 s_m}{l_m}, \quad (8)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic constant, w_2 is the number of turns in the secondary winding, and s_m and l_m are the cross sectional area and the mean length of the magnetic conductor.

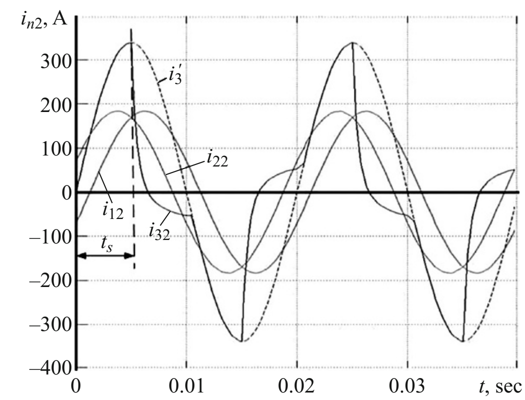

Fig. 7. Side currents for saturation of current transformer TT3 and $t_s = 5$ msec, $T_{2s} = 0.5$ msec and $\delta_k = 45°$: i_{12}, i_{22}, and i_{32} are the secondary current of the sides of the differential protection for TT1, TT2, and TT3 respectively, and i_3 the reduced primary current of TT3.

As an example we will consider a type TVT-35M current transformer with a transformer ratio of 3000/5, having the following parameters: $w_2 = 600$, $r_{w.2} = 1.58\ \Omega$, $s_m = 46.8 \times 10^{-4}$ m^2, and $l_m = 0.88$ m [6]. The load resistance rl is taken as 1.2 Ω. Calculations using formulas (8) and (7) gave the following results: $L_{0s} = 2.41 \times 10^{-3}$ H and $T_{2s} = 0.86$ msec. The built-in TVT-35M current transformer has a comparatively high value of s_m. It may be less for other types of current transformers. As a consequence of this, the value of T_{2s} is also reduced. The calculated value of T_{2s} is taken to be 0.5 msec, with a certain margin.

We will consider the modeling of the operation of a current transformer when saturated using the example of a circuit with the need for braking from three sides (Fig. 6).

Consider the process of saturation of a current transformer, the primary current of which when there is a short circuit is outside the region of action of the protection — the greatest. The nominal limit multiplicity with respect to the accuracy of the TVT-35M current transformer for a nominal load of 1.2 Ω is 24. In order to obtain $t_s = 5$ msec we specified the effective value of the primary current of the current transformer to be 144 kA. The maximum value of the secondary current of the transformer for $t_s = 5$ msec is then

$$i_{32\,\max} = \frac{\sqrt{2} \times 144 \times 10^3}{3000/5} = 339 \text{ A}.$$

The changes in the side currents with time are shown in Fig. 7.

The form of the curve of the secondary current i_{32} is close to the form of the curve obtained on the physical model of the current transformer, which ensures acceptable accuracy of the calculation of the first harmonic based on a Fourier filter.

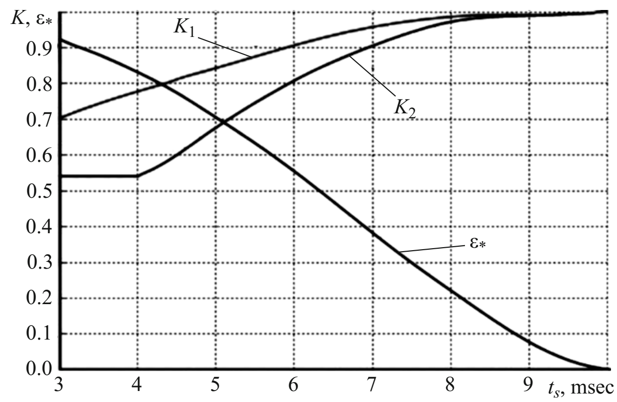

Fig. 8. Graph of the reduction factors of the braking current K and the relative total error of the current transformer as a function of the time t_s.

Investigations have shown that the braking values of the digital differential protections depend on such factors as:

— the phase difference of the currents of the controlled sides δ_k;

— the time to saturation t_s;

— the attenuation time constant of the exponential component T_{2s}.

In order to estimate the degree of reduction of the braking current, we modeled algorithms for calculating the braking values given by formulas (1) and (2).

In Fig. 8 we have drawn a graph of the reduction factors of the braking current against the time to saturation of the core of the current transformer for the first (K_1) and for the second (K_2) formulas for calculating the braking quantity. As can be seen, the calculation of the braking quantity using formula (1) is more convenient in view of the high value of the braking current.

The errors in the functioning of the current transformer in the steady mode is usually estimated by calculating the total error å. We therefore calculated the relative total error of the current transformer using the formula obtained under the condition that $T_{2s} \to 0$ [7],

$$\varepsilon_* = \sqrt{1 + \frac{\sin 2\omega t_s - 2\omega t_s}{2\pi}}. \tag{9}$$

The results of the calculations of ε_* using formula (9) are shown in Fig. 8. If we take the minimum (calculated) time $t_s = 4$ msec, we obtain the following:

— the total relative error ε_* reaches 0.83;

— the reduction factor of the braking current, calculated from formula (1), is 0.78;

— the reduction factor of the braking current, calculated from formula (2), is 0.53.

It is of interest to obtain the relation $t_s = f(I_{sc*})$. To do this we will write the expression for the short-circuit current in the general form

$$i_1 = I_{1m}[e^{-t/T_1}\cos\psi - \cos(\omega t + \psi)], \tag{10}$$

where T_1 is the time constant of the primary circuit and ψ is the initial phase of the EMF of the electric system.

Formula (10) gives sufficient accuracy when $T_1 \geq 2T$, where T is the period of the supply frequency.

For a practically resistive load of the current transformer and the short-circuit current, using expression (10) we obtain the following equation, containing the required quantity t_s:

$$\frac{B_{s.\mathrm{n}} - B_r}{B_m} = \omega T_1 (e^{-t_s/T_2} - e^{-t_s/T_1})\cos\psi +$$

$$+ \sin\psi\, e^{-t_s/T_2} - \sin(\omega t_s + \psi), \tag{11}$$

where $B_{s.\mathrm{n}}$ is the induction of the nominal saturation of the current transformer magnetic conductor, B_r is the residual induction and B_m is the calculated amplitude of the harmonic component of the induction.

Equation (11) can also be used to find ts under steady conditions. In this case, we must assume $\psi = 0.5\pi$. Moreover, it is necessary to take the following into account:

— in modern current transformers the time constant T_2 up to the instant of saturation is quite high (as a rule, not less than 5 sec), and hence the exponential factor in the second term on the right-hand side of Eq. (11) for short ts can be taken to be equal to 1;

— under steady conditions, reverse magnetization of the magnetic conductor of the current transformer from $-B_{s.\mathrm{n}}$ to $B_{s.\mathrm{n}}$ occurs (and vice versa), and hence we must assume that $B_r = -B_{s.\mathrm{n}}$. Taking this into account, we obtain the equation

$$2B_{s.\mathrm{n}}/B_m = 1 - \cos\omega t_s,$$

the solution of which has the form

$$t_s = \frac{T}{2\pi}\arccos\left(1 - \frac{2B_{s.\mathrm{n}}}{B_m}\right). \tag{12}$$

Formula (12) is inconvenient for practical calculations, so we will use the equation obtained in [8]:

$$B_{s.\mathrm{n}}/B_m = K_1/I_{sc*}. \tag{13}$$

For grade 3411 – 3413 steels we obtain $B_{s.\mathrm{n}} \approx 1.8$ T.

Taking (13) into account we finally obtain

$$t_s = \frac{T}{2\pi}\arccos\left(1 - \frac{2K_1}{I_{sc*}}\right). \tag{14}$$

Formula (14) holds when $K_l/I_{sc*} \leq 1$. The results of calculations for $T = 20$ msec are presented below.

I_{sc*}/K_l	t_s, msec
1.0	10.0
1.1	8.0
1.2	7.3
1.5	6.1
2.0	5.0
2.5	4.36
3.0	3.9

Formula (9) was obtained assuming an idealized scheme of the functioning of the current transformer, according to which, when $t_s = 10$ msec, we have $\varepsilon_* = 0$. When $(I_{sc*}/K_l) = 1$, we obtain $\varepsilon_* = 0.1$. It follows from this that formula (9) is approximate. It can be used when $t_s \leq 8$ msec and, correspondingly, when $(I_{sc*}/K_l) \geq 1.1$.

As follows from formulas (11) and (13), under transient conditions of the external short circuit, saturation of the current transformer, due to the effect of the aperiodic component of the current, may also occur when $(I_{sc*}/K_l) < 1$. Then, a second harmonic will appear in the differential unbalance current. Digital differential protection of block transformers usually have a blocking setting with respect to the second harmonic in the range 10 – 14%, which considerably facilitates the tuning out of the transient unbalance currents. Hence, the transient mode when there is an external short circuit is not decisive when choosing the braking method.

CONCLUSIONS

1. When there is a short circuit at the sealing off of the main transformer the shift angle of the phases between the currents from the generator side and from the block transformer side increases when the length of the line between the station and the system increases and, as a rule, does not exceed 46°.

2. Saturation of the cores of the current transformer of the damaged connection under steady state conditions of the external short circuit leads to a reduction of the braking quantities, calculated both from formula (1) and from formula (2). It is preferable to calculate the braking current using formula (1), since the braking current obtained using this formula is greater than that given by formula (2). For the minimum (theoretical) value $t_s = 4$ msec, the overall error of the current transformer å is approximately 80%.

REFERENCES

1. A. M. Dmitrenko, “Differential protection of transformers and autotransformers,” *Élektrichestvo*, No. 2 (1975).
2. G. Ziegler, *Digital Differential Protection Devices. Principles and Areas of Application* [Russian translation], Znak, Moscow (2008).
3. “*RusHydro*” *JSC Standard. Determination of Preliminary Technical Solutions on the Power Distribution of Electric Power Plants. Order 752/1p-213*, *November 24*, *2008* [in Russian].
4. V. A. Venikov, *Transient Electromechanical Processes in Electric Systems. A Textbook* [in Russian], Vysshaya Shkola, Moscow (1985).
5. A. D. Drozdov and S. L. Kuzhekov, “The form of the secondary current of protected current transformers under transient and steady conditions,” *Élektrichestvo*, No. 1 (1971).
6. E. P. Korolev and E. M. Liberzon, *Calculations of the Permissible Loads in the Current Circuits of Relay Protection* [in Russian], Énergiya, Moscow (1980).
7. V. V. Platonov (ed.), *Electric Circuits with Ferromagnetic Components in Relay Protection* [in Russian], Énergoatomizdat, Moscow (1986).
8. A. M. Dmitrenko and A. Yu. Sinichkin, “High-speed differential protection of busbars based on the REB670 device,” *Élektrotekhnika*, No. 1 (2011).