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ON THE REQUIREMENTS OF CURRENT TRANSFORMERS IN DIFFERENTIAL PROTECTION OF TRANSFORMERS AT ELECTRIC POWER STATIONS

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The problem of picking protective current transformers (CT) in order to ensure proper functioning of differential protection in transient regimes is examined. It is proposed that the accuracy limit factor K_{lim} referenced to the nominal current of a power transformer be used as the main parameter in choosing CT. A method is presented for calculating K_{lim} as a function of the time to saturation t_s, the decay time constant of the aperiodic component of short-circuit (SC) current, and the residual induction and current of external SC. It is shown that increasing K_{lim} results in smaller CT errors in the time interval of the saturated state of a magnetic circuit. It is pointed out that the effect of screening must be taken into account in finding K_{lim} for CT which do not have a proper primary winding and are arranged in phase with screened conductors.

Keywords: current transformer; core saturation; accuracy limit factor; resistance; secondary circuit; differential protection; residual induction; screening.

Differential protection is the main form of protection (functions in complex microprocessor protection) of transformers. The response time of the sensitive organs of such protection on sinusoidal current is 25 – 30 msec, which presents certain problems for operational stability in transient regimes of external short circuits (SC).

According to [1] the CT requirements of differential protection of transformers are formulated as follows: the total error CT ε in a steady-state regime in the presence of external SC should not exceed 10%. The calculation of the total error ε in design calculations is associated with certain difficulties, so that the concept of the accuracy limit factor K_{lim} of CT [2, 3] is used; this factor can be calculated from the expression [3]

$$K_{\text{lim}} = \frac{\omega B_{\text{lim}} w_2 s_{\text{m}}}{\sqrt{2} I_{2\text{nom}} z_2}, \qquad (1)$$

where ω is the angular frequency; $B_{\text{lim}} = 1.8 - 1.85$ T is the maximum value of the induction when the magnetic circuit of the CT is comprised of cold-rolled electrotechnical steel; w_2 is the number of turns of the secondary winding; sm is the cross-sectional area of the magnetic-circuit steel; $I_{2\text{nom}}$ is the secondary nominal current; $z_2 = |Z_{\text{win2}} + Z_{\text{load}}|$ is the modulus of the complex resistance of the secondary circuit of the CT; Z_{win2} is the complex resistance of the secondary winding of the CT in a T-shaped equivalent circuit; and, Z_{load} is the complex impedance of the load.

As a rule CT with wound ring-shaped magnetic circuits are used in the protection schemes of transformers. The secondary winding is wound uniformly on the magnetic circuit. Taking this into account the reactance of the secondary winding x_{win2} (leakage resistance) is less than the resistance r_{win2} [3]. Finally we can write

$$z_2 = |r_{\text{win2}} + r_{\text{load}} + jx_{\text{load}}|. \qquad (2)$$

According to GOST 7746–2001 [4] the resistance r_{win2} should be given in the CT data sheet.

Current transformers for relay protection are manufactured with 5R or 10R class accuracy; correspondingly, the accuracy limit factor is designated as K_5 or K_{10}. As indicated above, in the relation (1) $B_{\text{lim}} = 1.8 - 1.85$ T. The values of K_5 and K_{10} differ little, and a generalized concept K_{lim} [which is used in Eq. (1)] can be introduced with error ≤5%.

The generally accepted practice in the calculation of SC currents is to use as the baseline quantity the nominal current $I_{\text{nom.c}}$ of a power transformer [5]. Moreover, $I_{\text{nom.c}}$ is also used as baseline current in specifying the settings of the differential protection of a power transformer. On this basis it

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is helpful to introduce a concept of the accuracy limit factor referenced to $I_{\text{nom.c}}$:

$$K'_{\text{lim}} = \frac{I_{\text{1nom.CT}}}{I_{\text{nom.c}}} K_{\text{lim}}, \tag{3}$$

where $I_{\text{1nom.CT}}$ is the primary nominal current of the CT, and to formulate in the following form the requirement of CT in the steady-state regime:

$$K'_{\text{lim}} \geq I_{\text{SC}*}, \tag{4}$$

where $I_{\text{SC}*} = I_{\text{SC}}/I_{\text{nom.c}}$.

According to [4] CT manufacturers must set the nominal accuracy limit factor K_{nom} for a specified nominal power of the secondary load S_{2nom}. As a rule the values of K_{nom} must lie in the range 5 – 30. However, it is acceptable to manufacture CT with larger values of K_{nom}. For example, for a number of CT manufacturers $K_{\text{nom}} = 40$.

The modulus of the nominal resistance of the secondary load of the CT can be calculated as

$$z_{\text{load. nom}} = S_{\text{2nom}} / I^2_{\text{2nom}}.$$

The nominal value of $z_{\text{load.nom}}$ is specified for $\cos\varphi_{\text{load}} = 0.8$. The nominal values S_{2nom} must correspond to the series: 3, 5, 10, 15, 20, 25, 30, 50, 60, 75, and 100 V · A.

On the basis of the expression (2) with $\cos\varphi_{\text{load}} = 0.8$ we can write

$$z_{\text{2nom}} = \sqrt{r^2_{\text{win2}} + 1.6 r_{\text{win2}} z_{\text{load. nom}} + z^2_{\text{load. nom}}}. \tag{5}$$

The resistance of the input current circuits of the case holding the microprocessor protection of a transformer is close to the active resistance. Moreover, it is significantly less than the resistance of the conductors of the control cable connecting the secondary winding of the CT and the input circuits of the case. On this basis the working load resistance rload. work of the CT can be calculated as a purely active resistance. It depends on the scheme used to connect the secondary windings of the CT group and the form of the SC and can be calculated by well-known methods, for example, the method expounded in [2].

In summary, in using a case for the microprocessor protection we can write

$$z_2 = r_{\text{win2}} + r_{\text{load.calc}}. \tag{6}$$

The values of K_{lim} can be calculated with adequate accuracy using the relation (1) and the number of turns w_2 and the cross-section s_{m} of the magnetic circuit, which was done in [2]. However, under present conditions it is not always possible to know w_2 and s_{m}, so that the actual accuracy limit factor for CT is best found by using the values of K_{nom} and $z_{\text{load.nom}}$. Substituting into the relation (1) the values of z_2 according to the relations (5) and (6) we obtain

$$K_{\text{lim}} = K_{\text{nom}} \frac{\sqrt{r^2_{\text{win2}} + 1.6 r_{\text{win2}} z_{\text{load. nom}} + z^2_{\text{load. nom}}}}{r_{\text{win2}} + r_{\text{load.calc}}}. \tag{7}$$

Under the condition (4) there is practically no saturation of the magnetic circuit of the CT in the steady state. However, in a transient regime saturation can obtain as a result of the influence of the aperiodic component of the SC current. For SC near the generator at an electric power station the harmonic component of the SC current is damped. A short circuit is considered to be nearby if in the first period T after the appearance of the SC the ratio of the amplitude of the harmonic component of the SC current to the amplitude of the nominal current of the generator is ≥2 [5].

As will be shown below, it is useful to specify the time to CT saturation in a transient regime as $\leq 0.5T$. The damping of the harmonic component of the SC current can be neglected and the following simplified expression used [6]:

$$i_1 = I_{1m}[e^{-t/T_1} \cos\psi - \cos(\omega t + \psi)], \tag{8}$$

where T_1 is the damping time constant of the aperiodic component of the SC current; ψ is the initial phase of the supertransitional emf of the generator or system; I_{1m} is the amplitude of the primary current of the CT.

The relation (8) gives adequate accuracy for $T_1 \geq 2T$ (which holds for SC near electric power stations).

The time t_{s} to saturation of CT in a transient regime with an active load of the CT and primary current in accordance with the expression (8) can be found using the equation [6]

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

$$+ \sin\psi e^{-t_s/T_2} - \sin(\omega t_s + \psi), \tag{9}$$

where $B_{s.\text{cond}}$ is the induction at conditional saturation of the magnetic circuit (when using a rectified magnetization characteristic); B_r is the residual induction; B_m is the amplitude of the harmonic component of the induction, calculated under the condition that there is no saturation of the magnetic circuit; T_2 is the time constant of the secondary circuit of the CT with an unsaturated magnetic circuit.

It is helpful to rewrite Eq. (9) in the form

$$\frac{B_{s.\text{cond}}(1 - B_{r*})}{B_m} = K_{Ba}, \tag{10}$$

where $B_{r*} = B_r / B_{s.\text{cond}}$.

The factor K_{Ba} equals the right-hand part of Eq. (9). It takes account of the increase in the induction in a transient

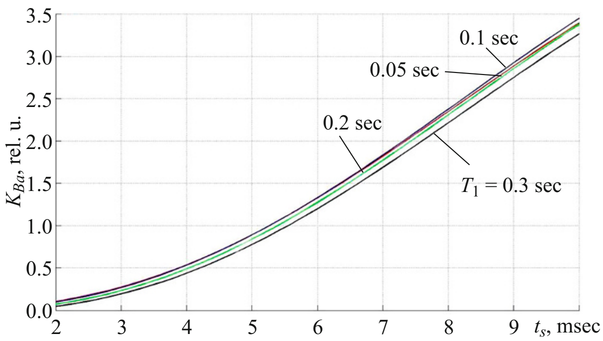

Fig. 1. Plots of the factor K_{Ba} versus the time to saturation t_s with the initial phase of the supertransitional emf of the generator 30° and different values of the damping time constant of the periodic component of the SC current T_1.

regime as a result of the effect of the aperiodic component of the primary current.

It is easily shown on the basis of [6] and relation (3) that the following relation holds with adequate accuracy:

$$\frac{B_{s.\mathrm{cond}}}{B_m} = \frac{K'_{\mathrm{lim}}}{I_{\mathrm{SC}*}}. \tag{11}$$

Using the relations (10) and (11) we obtain the following condition for picking the reduced accuracy limit factor of the CT:

$$K'_{\mathrm{lim}} \geq \frac{K_{Ba} I_{\mathrm{SC}*}}{1 - B_{r*}}. \tag{12}$$

For $K_{Ba} = 1$ and $B_{r*} = 0$ the relation (12) coincides with the relation (4) for the steady state regime.

In accordance with the relation (9) the factor K_{Ba} is a function of the time constants T_1 and T_2, the time to saturation t_s, and the initial phase ψ. So as not to overvalue the requirements now used in Russia it is best to use $t_s \leq 10$ msec. The time constant T_2 to saturation of modern CT is quite large (of the order of 5 sec [6]). For this reason its effect on the factor K_{Ba} for $t_s \leq 10$ msec is very small.

The time constant T_1 with SC in lines near the high-voltage busses of electric power stations is usually ≥0.05 sec. Analysis of the functions $K_{Ba} = f(T_1)$ at ψ = 0 with T_1 ranging from 0.05 to 0.3 showed that the effect of T_1, though appreciable, is not decisive. Ultimately two quantities have the greatest effect on the value of K_{Ba}: t_s and ψ.

Ordinarily, in studying transient unbalance currents of differential protection the case ψ = 0 is studied as the worst case because the highest unbalance current obtains in this case [7]. However, for modern digital differential protection of transformers the time t_s to saturation of CT is significant in and of itself [6, 8]. In this connection the dependences $K_{Ba} = f(t_s)$ with T_1 ranging from 0.05 to 0.3 sec and ψ from 0 to 60° were studied. These studies showed that for differential protection of transformers it is desirable to pick ψ = 30° as the working value, since in this case the initial value of the aperiodic component of the SC current decreases by only 13% and the factor K_{Ba} increases by 15 – 30%. Plots of the functions $K_{Ba} = f(t_s)$ at ψ = 30° and different values of T_1 are presented in Fig. 1.

The curves start at t_s = 2 msec, since it is assumed that in any case t_s must be at least 2 msec (0.002 sec). Using the indicated curves the values of K_{Ba} can be found for specified values of T_1 and t_s. In the derivation of the expression (12) it was assumed that $B_{s.\mathrm{cond}} = B_{\mathrm{lim}}$ = 1.8 – 1.85 T.

The use of CT with a closed ring-shaped magnetic circuit without an air gap (class TPS or TPX in the terminology of IPC 60044-6) is under consideration. Here we have in mind cold-rolled steels 3411 – 3414. The working maximum value of the residual induction in a cycle of unsuccessful automatic re-connection (ARC) can be used for such steels:

$$B_{r*} = B_r/B_{\mathrm{lim}} = 1.2/1.85 = 0.65.$$

The indicated value of B_{r*} can be used in the calculation of K_{lim} on the high-voltage (HV) side of a block transformer (SC on the HV busses or on a line connected to busses). ARC is usually not used on the low-voltage (LV) side of the block transformer or an internal-needs transformer (INT). Moreover, the fact that an SC is relatively rare in the indicated cases must be taken into account. On this basis it can be assumed that $B_{r*} \approx 0.3$.

As one can see from the relation (7) the ratio $K_{\mathrm{lim}}/K_{\mathrm{nom}}$ depends on the ratio $r_{\mathrm{load.calc}}/r_{\mathrm{win2}}$. As a result of this in CT with secondary nominal current 1 A (under otherwise equal conditions) the value of K_{lim} can be greater than for CT with secondary nominal current 5 A. On this basis the working values of t_s must be specified as follows:

7 – 8 msec — for CT with secondary nominal current 5 A;

10 msec — for CT with secondary nominal current 1 A.

Branching to INT is, as a rule, limited in terms of the use of CT with primary nominal current significantly higher than the nominal INT current, for example, for CT built into INT. Thus, $I_{\mathrm{1nom.CT}}$ is found to be much less than $I_{\mathrm{nom.c}}$ of a block transformer on the LV side. It is evident from the expression (3) that in this case K'_{lim} is less than K_{lim}. In such cases the condition (4) must be used. Now, K_{Ba} can be calculated from the relation

$$K_{Ba} = (1 - B_{r*}) = 1 - 0.3 - 0.7 \tag{13}$$

and the time to saturation of the CT can be found from the curves in Fig. 1.

Very large currents can obtain in the presence of SC on the branch to INT [6]. In such cases it may be necessary to use CT with secondary nominal current 1 A in order to satisfy the condition (4).

An increase of K_{lim} also leads to reduction of CT errors in the time interval of the saturated state of the magnetic circuit. This is evident from the following. The time constant T_2 of the secondary circuit of the CT on the interval of the saturated state of the magnetic circuit can be calculated using the approximate relation [7]

$$T_{2s} \approx \frac{\mu_{\text{diff}} w_2^2 s_{\text{m}}}{l_{\text{av}}(r_{\text{win2}} + r_{\text{load.calc}})}. \quad (14)$$

where μ_{diff} is the differential magnetic permeability (found from the saturated part of the rectified magnetization characteristic); I_{av} is the average length of the magnetic line.

Using the relation (1) it is easy to show that the equality (14) can be written in the following form:

$$\omega T_{2s} \approx \frac{\mu_{\text{diff}} I_{1\text{imp. nom}m} K_{\text{lim}}}{B_{\text{lim}}}. \quad (15)$$

where

$$I_{1\text{imp. nom}m} = \frac{\sqrt{2} I_{1\text{nom.CT}} w_1}{l_{\text{av}}}. \quad (16)$$

According to the relation (16), $I_{1\text{imp.nom}m}$ is the amplitude of the magnetic field intensity in the core with nominal primary current and an open secondary winding of the CT.

The calculated value of μ_{diff} decreases with increasing maximum value of the magnetic field intensity $H_{\max}$ (transient processes with $H_{\max} \geq 1000$ A/m are being studied). In the presence of saturation of the magnetic circuit of the CT in a transient regime and $t_{\text{s}} \leq 10$ msec it can be assumed that approximately

$$H_{\max} \approx K_{\text{imp}} I_{\text{SC}*} I_{1\text{imp. nom}m} \frac{I_{\text{nom.c}}}{I_{1\text{nom.CT}}}. \quad (17)$$

where K_{imp} is the impact factor.

The value of $I_{1\text{imp.nom}m}$ is a parameter of the CT. The value of $H_{\max}$ depends on the ratio $I_{\text{nom.c}}/I_{1\text{nom.CT}}$ and therefore on the conditions of application of CT.

Analysis of the relations (15) – (17) taking account of the dependence $\mu_{\text{diff}} = f(H_{\max})$ showed that T_2s increases with increasing value of the parameters K'_{lim}.

Knowing the product ωT_{2s}, the following relations can be used to calculate the relative amplitude of the primary harmonic of the magnetization current I_{0m*} and the secondary current I_{2m*} (the amplitude of the harmonic component of the primary current, referred to the secondary winding w_2 is taken as the baseline value):

$$I_{0m*} = \frac{1}{\sqrt{1 + (\omega T_{2s})^2}}; \quad (18)$$

$$I_{2m*} = \frac{\omega T_{2s}}{\sqrt{1 + (\omega T_{2s})^2}}. \quad (19)$$

As the T_{2s} increases, the current I_{2m*} decreases [relation (18)] and the current I_{2m*} increases with increasing K_{lim}.

As one can see from the relations (3) and (7) the reduced accuracy limit factor K'_{lim} depends on the ratio $I_{1\text{nom.CT}}/I_{\text{nom.c}}$ and the working resistance of the load $r_{\text{load.calc}}$. The latter depends on the connection scheme of the secondary windings of the CT and on the form of the SC [2]. On this basis it is hardly possible to consider the manufacturer's design requirement of a definite level of transformation on the interval of the saturated state of the core (as assumed in [8]).

It would be more helpful to require the CT manufacturer to provide in the guidelines the dependence $B_{\text{lim}} = f(H_{\max})$ of the magnetic circuit at least up to the value $H_{\text{lim}} = I_{1\text{imp.nom}m}$ (but ≥3000 A/m). This would make it possible to evaluate more accurately the value of μ_{diff} in the region of the saturated state of the magnetic circuit of the CT. It is known that μ_{diff} in the saturation region is found to be greater when using the worst grades of cold-rolled electrotechnical steels, for example 3411–3413.

It should be noted that the CT used on the generator voltage can have quite large values of the parameter $I_{1\text{imp.nom}m}$. For example, according to the relation (16) TSH20 CT manufactured by Élektroapparat JSC (St. Petersburg) has the following value of the indicated parameter for $I_{1\text{nom.CT}} =$ = 16,000 A:

$$I_{1\text{imp. nom}m} = \frac{\sqrt{2} \cdot 16{,}000}{2.59} = 8736 \text{ A/m}.$$

However, no information on the manufacturer's characteristics of the magnetization is presented.

On the whole it should be noted that under present conditions the problem of determining the form of the curve of the secondary current of a CT in transient regimes can be solved by computer modeling (based on numerical methods of solving the corresponding nonlinear differential equations). In addition, the mutual influence of CT in the three-phase group in a transient regime in saturation of one or several CT can be taken into account.

The use of the generalized parameter K'_{lim} makes it possible to determine more quickly the most difficult (working) regimes of external SC and thereby increase the effectiveness of simulation modeling.

There is one other problem that should be mentioned. Electricity is transmitted from the generator to the transformer using conductors screened in each phase (at nominal currents ≤2000 A) [9]. This is done using CT without a proper primary winding, which are built into the conductor, for example TSH20 CT on primary nominal currents from 8000 to 16,000 A, TSHV24 CT on primary nominal currents 24,000 and 30,000 A, and others.

The distances between the phase axes are comparatively small. For example, for a conductor in the circuit of a TVV-500 turbo generator at nominal voltage 20 kV the distance between the axes is 1400 – 1500 mm. The magnetic field of the neighboring phase (neglecting screening) can

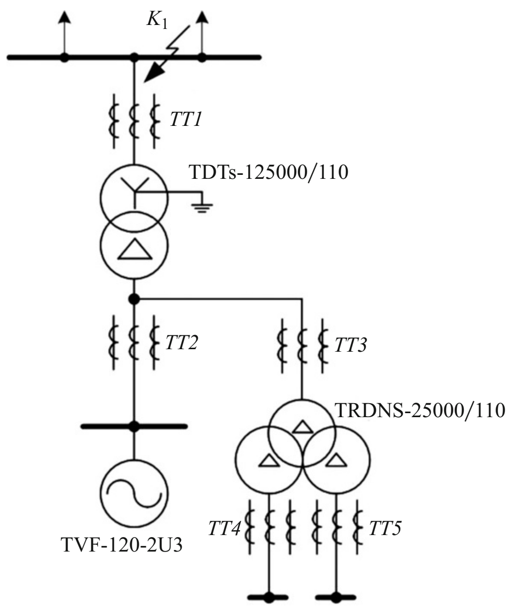

Fig. 2. Working circuit for picking CT on the HV side of the block transformer.

lead to saturation of the magnetic circuit of the CT and reduction of the accuracy limit factor K_{lim} [compared with the value calculated from the expression (1)].

According to GOST 7746–2001 [4], in checking the errors of CT without a proper primary winding the CT must be included in the current circuit (taking account of the magnetic field of the neighboring phase). This leads to a significant reduction of the accuracy limit factor. For example, the TSH20 CT mentioned above on primary nominal currents ranging from 8000 to 16000 A have the same accuracy limit factor 9. For the TSHV24 CT manufactured by Élektroapparat JSC the parameter values are:

— nominal secondary load $S_{\text{load}} = 100$ V · A;

— $K_{\text{nom}} = 5$ with primary nominal current 24,000 A; and,

— $K_{\text{nom}} = 6$ with primary nominal current 30,000 A.

For loads ranging from 1 to 4 Ω the values of the accuracy limit factors remain unchanged.

When the CT is placed beneath the screen sheath the effect of ac magnetic field of a neighboring phase decreases 40–100-fold (depending on the parameters of the screen) [9]. The accuracy limit factor K_{lim} increases considerably. It can be calculated approximately from the relation (1).

For example, TSHV24 CT with transformation coefficient 24000/5 has the following technical data: $w_2 = 4800$; $s_m = 6.4 \times 10^{-4}$ m²; $r_{\text{win2}} = 5.2$ Ω.

Using the relations (5) and (1), for $S_2 = S_{2\text{nom}}$ we calculate

$$z_{2\,\text{nom}} = \sqrt{5.2^2 + 1.6 \times 5.2 \times 4 + 4^2} = 8.73\ \Omega;$$

$$K_{\text{nom}} = \frac{314 \times 1.85 \times 4800 \times 6.4 \times 10^{-4}}{\sqrt{2} \times 5 \times 8.73} = 28.9.$$

The value obtained for K_{nom} is approximately a factor of 6 greater than the value indicated in the technical documentation for CT (obtained from test_s without taking account of screening). It follows that in the new version GOST 7746–2001 for CT installed in screened conductors of each phase, the norm of the CT tests in a SC circuit should be eliminated in order to find K_{nom}. After this change the relation (1) can be used to calculate K_{lim}.

At present the working resistance of the load can be adopted on the basis of the condition $r_{\text{load.calc}} \le$ $\le (0.5 - 1.0) z_{\text{load.nom}}$. The coefficient 0.5 should be used for TSHV24 CT; for TSH20 CT it can be assumed that $r_{\text{load.calc}} \le (0.8 - 1.0) z_{\text{load.nom}}$. This will give an acceptable error for the indicated CT in transient regimes.

Example. We shall use the described recommendations in picking CT on the HV side of the block transformer, shown in Fig. 2.

The calculated regime in picking CT_1 is SC on 110 kV busses. We have:

for three-phase SC: $I_{k*}^{(3)} = 3.77$, $T_1^{(3)} = 0.2$ sec;

for one-phase SC: $I_{k*}^{(1)} = 4.53$, $T_1^{(1)} = 0.1$ sec.

To determine the working value of the secondary load of the CT it is necessary to know the parameters of the neighboring conductors and transient resistance of the connective contacts in the current circuits:

$\rho = 1.75 \times 10^{-8}$ Ω/m – resistivity of copper;

$s = 2.5 \times 10^{-6}$ m² — cross section of the connecting wires;

$l = 100$ m — length of connective wires;

$r_{\text{trans}} = 0.1$ Ω — transient resistance of the contacts.

The minimum primary nominal current of the CT is usually picked using the condition

$$\min(I_{1\,\text{nom.CT}}) \ge \sqrt{3} I_{\text{nom.c}} = \sqrt{3} \times 596 = 1032 \text{ A}.$$

We pick a TRG-110-1200/5 CT with sulfur hexafluoride insulation for an exterior setup manufactured by Uralélektrotyazhmash. The parameters of this CT are:

transformation factor $k_{\text{CT}} = 1200/5$;

nominal power of the secondary winding $S_{2\text{nom}} =$ $= 40$ V · A;

nominal accuracy limit factor $K_{\text{nom}} = 20$;

cosine of the load angle $\cos \varphi_{\text{load}} = 0.8$;

dc resistance of the winding w_2 $r_{\text{win2}} = 0.35$ Ω.

The modulus of the nominal resistance of the secondary load of the CT

$$z_{\text{load.\,nom}} = \frac{S_{2\,\text{nom}}}{I_{2\,\text{nom.CT}}^2} = \frac{40}{5^2} = 1.6\ \Omega.$$

Using the relation (5) we calculate the modulus of the complex resistance of the secondary circuit of the CT on the basis of the manufacturer's data sheet

$$z_{2\text{nom}} = \sqrt{0.35^2 + 1.6\times 0.35\times 1.6 + 1.6^2} = 1.89\ \Omega.$$

The resistance of a conductor in a control cable with $s_{\text{cd}} = 2.5\ \text{mm}^2$

$$r_{\text{phase}} = \frac{\rho l}{s_{\text{c}}} = \frac{1.75\times 10^{-8}\times 100}{2.5\times 10^{-6}} = 0.7\ \Omega.$$

In the event of a three-phase SC the load on the CT is determined successively by the connected resistances of the conductor of the control cable and the transient resistance of the contacts. In the case of a single-phase SC the load resistance increases owing to the current flow over the zeroth conductor of the control cable. On this basis we have:

$$r^{(3)}_{\text{load.calc}} = r_{\text{phase}} + r_{\text{trans}} = 0.7 + 0.1 = 0.8\ \Omega;$$

$$r^{(1)}_{\text{load.calc}} = 2(r_{\text{phase}} + r_{\text{trans}}) = 2(0.7 + 0.1) = 1.6\ \Omega.$$

It is evident from the relation (7) that the real accuracy limit factor decreases with increasing $r_{\text{load.calc}}$. Therefore, the single-phase SC regime should be taken as the working regime.

We shall check the chosen CT for satisfaction of the requirement (12) in the single-phase SC regime.

Using the relations (5) and (7) we calculate the real accuracy limit factor of the CT as

$$K_{\text{lim}} = 20\frac{1.89}{0.35+1.5} = 20.4.$$

Using the relation (3) we find the reduced accuracy limit factor

$$K'_{\text{lim}} = \frac{1200}{596}20.4 = 41.1.$$

Now we take the time to saturation of the CT as $t_{\text{s}} =$ = 8 msec, and using Fig. 1 we find for the time constant $T_1 =$ = 0.1 sec the induction intensification coefficient

$$K_{Ba} = 2.37.$$

In the transient regime the condition (12) should hold for the CT:

$$K_{\text{lim}} \geq \frac{2.37\times 4.53}{1-0.65} = 30.7.$$

The result shows that the chosen CT follows the check condition in the transient regime.

It is easily shown that in this case the value of K_{lim} in the event of a three-phase SC is found to be 66.2. The value of K_{lim} is good from the standpoint of securing fast operation of the differential protection in the event of a three-phase SC in the protected zone.

CONCLUSIONS

1. The errors in the transient regime in the time interval of the saturated state of the magnetic circuit depends not only on the parameters of the CT [w_1, w_2, s_{m}, l_{av}, r_{win2}, $B_{\text{lim}} =$ $= f(H_{\max})$] but also the conditions of its application (ratio $I_{\text{1nom.CT}}/I_{\text{nom.c}}$, rload, work, and others). In this connection it is inadvisable to give specifications to CT manufacturers on basis of some errors (for example, in terms of the first harmonic of the secondary and magnetization currents).

2. It is more effective to formulate the requirements of CT using a generalized parameter K_{lim}. On this basis a method was developed to calculate K_{lim} as a function of the time t_{s} up to saturation of the magnetic circuit, the residual induction Br, and the relative value of the current of the external SC. It was shown that the use of high values of K_{lim} also leads to a reduction of the error of CT in the time interval of the saturated state of the magnetic circuit. It is important to note that the proposed method of calculating K_{lim} can be comparatively easily mastered at design organizations.

3. The form of the curve of the secondary current of CT in transient regimes is best determined by means of computer modeling. To this end CT manufacturers should be required to give in reference data sheet_{s} the function $B_{\text{lim}} = f(H_{\max})$ of the magnetic circuit at least up to $H_{\text{lim}} = I_{\text{1imp.nom}m}$ (but ≥3000 A/m).

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