



PS1 – S3-06



Sensitivity and Operation Speed of Protection Equipment and Power Transformers' Emergency Control Increase

Valery K. VANIN, Maxim G. POPOV, Stanislav O. POPOV
Saint Petersburg State Polytechnic University
Russia
PopovMG@eef.spbstu.ru

KEYWORDS

Interconnected power systems (IPS), transformer equipment, differential protection, bias currents forming algorithms, current transformer (CT), primary current reestablishment, magnetization current.

1 INTRODUCTION: PROBLEM NOWADAYS

Power supply system development is accompanied by rapid increase of transformer capacity injection on newly constructed and reconstructed substations 110-750 kV. In this connection power supply stability in interconnected power system is defined by the power supply equipment reliability to a considerable degree. According to [1,2] the increase to 18 % of the total economic and technological damage caused by spurious tripping and power transformers' protection refusal in consequence of their internal damages is observed.

It's explained by considerable cost (to 60-100 % from total cost) and longer (concerning standard term) duration of emergency repair of the powerful transformer. Besides, in most cases after emergency ignition the transformer is beyond repair, and the subsequent review of failure doesn't establish the initial reason of damage because of the great level of destructions, and as consequence doesn't allow introduction of necessary constructive changes directed on reliability improvement of power equipment.

In this connection the problem of operation speed and sensitivity increase and of power transformer protection is relevant and priority in the problem decision of electric equipment reliability work in interconnected power systems (IPS). Increase of speed and sensitivity of the main power transformers current direct-axis differential protection will afford to reduce level of their injuries, to exclude possibility of ignition and, as consequence to take down amortization expenses for repair.

Enhancement of power transformers' protection equipment should be carried out on the basis of the qualitative system analysis of transients in power supply system. Research of the physical phenomena in transformers at various damages into them and external switching is made with adequate mathematical models of the electric equipment using, which are considered a real arrangement of phase windings, their connection scheme and connection group, also their own nonlinearity and mutual inductances.

Methods of working out of the specified mathematical formulation of power transformers (autotransformers) were developed on «Power plants and automation of power supply systems» chair of the SEI HPE «Saint-Petersburg State Polytechnical University» [3].

The present research is devoted to the improvement of functional algorithms of bias and measurement of differential currents with application of the current transformers' mathematical description. Restoration of primary signals taking into account an error of measuring transformers is the most perspective direction in speed, sensitivity and selectivity of power transformers differential protection problem solution. As it is mentioned below this problem can't be solved without

quantitative and qualitative estimation of magnetization currents of, both the power transformer, and measuring current transformers (CT).

2 CURRENT TRANSFORMER ERROR INFLUENCE ON POWER TRANSFORMER DIFFERENTIAL PROTECTION OPERATION.

The power and current transformers magnetization currents' influence in transients can be of a variety character. The power transformer magnetization current reaches great values only at switching on small loading or idling. Thus in a current signal frequency spectrum a level of 2nd and 5th harmonics (fig. 1) would be strongly displayed, the occurrence of which point out to power transformer magnetization current increase.

It is important to notice that at startup CT can be saturated. As a result second harmonic level in secondary current signal is decreasing (curve 2, fig. 1) and thus there can be the transformer spurious tripping.

The power transformers' magnetization current practically is absent in short circuit modes and, as consequence, the protection unbalance current is defined by an CT magnetization current basically.

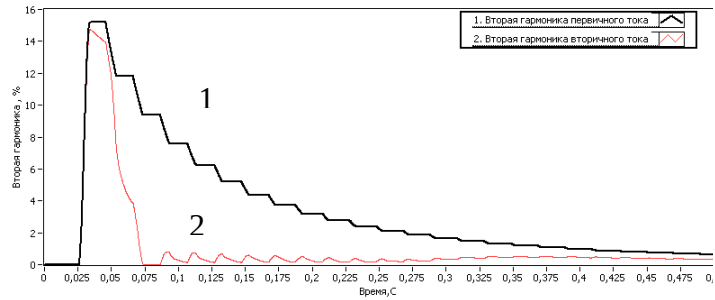


Fig. 1: Second harmonics changing during idling

$$i_{нб} = i_{2I} - i_{2II} = (i'_{1I} - i'_{\mu I}) - (i'_{1II} - i'_{\mu II}) = i'_{\mu T} + i'_{\mu II} - i'_{\mu I} + U'_{пнл} + f_{урз} \quad (1.)$$

where $i'_{1I}, i'_{2I}, i'_{\mu I}$ - reduced primary, secondary currents and the reduced value of a first branch

CT magnetizing current accordingly; $i'_{1II}, i'_{2II}, i'_{\mu II}$ - the second protection branch too;

$i'_{\mu T}$ - power transformer magnetization current; $U'_{олс}$ - accuracy as a result of on-load tap change; $f_{mрp}$ accuracy relay protection means, caused by ADC resolution, an error of calculations, etc.

Noncontiguous component of unbalance current characterized by ADC characteristics and OLTC regulating effect can be emphasized in (1) equation. As a rule, these unbalance current components are insignificant – a range of on-load tap changer of 16 %, and the ADC resolution error makes no more than 3 %. In the steady state the unbalance current is insignificant and with use sufficiently simple restrain methods necessary operating efficiency of differential protection is provided.

The relative unbalance current increases in transients with increase of protection branch current level. In such modes the instant error of current transformers increases to 70 % (fig 2.f) also value can reach more than 100 %. Thus instant (local) errors of CT $\varepsilon_{ст}$ it is calculated using an expression:

$$\varepsilon_{ст} = \frac{1}{I'_1} \frac{1}{T} \int_0^T (i'_1 - i_2)^2 dt$$

where I'_1 - reduced primary currents' rms value

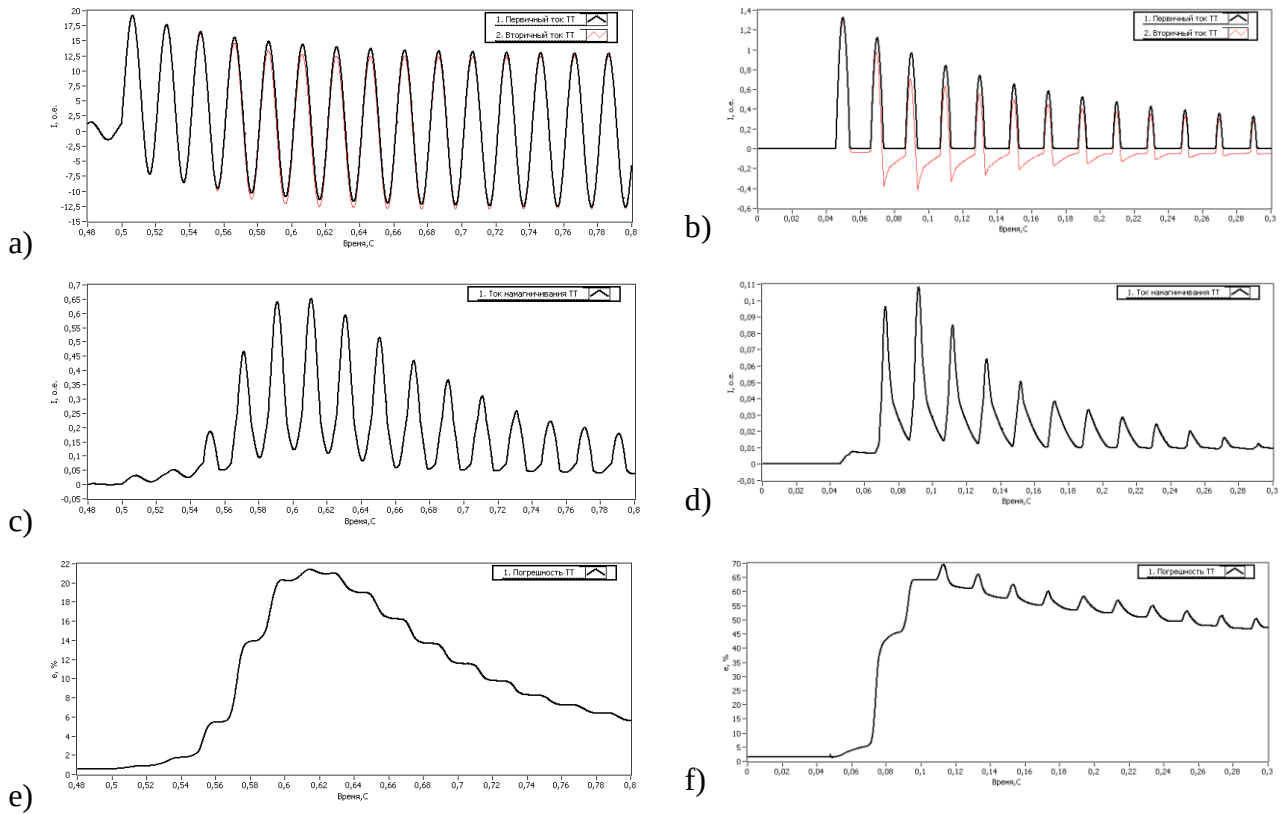


Fig. 2: CT transients

a, b) Primary (reduced) and secondary current during short-circuit and idling;
 c, d) Magnetization current during short-circuit and idling;
 e, f) CT full error during short-circuit and idling

Thereupon differential protection restraining is applied for sensitivity increase (fig. 3). As that differential protection operation condition is described, generally, by an inequality

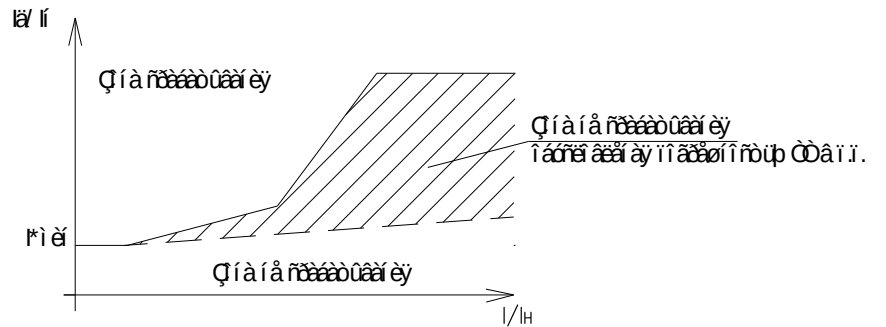


Fig. 3: Differential protection operation characteristic

$$I_d - I_{c.мин} - k_m I_m > 0$$

where I_d - differential current; $I_{c.мин}$ - min. operation protection current; I_m bias current;
 k_m - bias coefficient.

Thus the unbalance current magnitude depends not only on rate of a primary current, but also on the form of this signal. It leads to inconsistent requirements to deceleration currents forming and defines their great variety. The most effective are the deceleration signals received from differential protection branch currents. Following algorithms are widespread (tab. 1): the sum of absolute currents values of all branches, the maximum sum of positive and negative halfwaves of branch currents, the Difference of the sum of absolute values and the module of a differential current, the branch maximum current.

Name	Algorithm	$\left(\frac{I_d}{I_m}\right)_{\max}$			
		$\varepsilon_{CT} < 10\%$	$\varepsilon_{CT} = 20\%$	$\varepsilon_{CT} = 40\%$	$\varepsilon_{CT} = 60\%$
Sum of currents' absolute values of all branches	$\sum_{k=1}^N i_k $	0.06	0.2	0.38	0.61
Maximum sum of positive and negative half waves of branches' currents	$\max\{i_{noz}, i_{omp}\}$ $i_{noz} = 0,5 \cdot \sum_{k=1}^N (i_k + i_k), i_{omp} = 0,5 \cdot \sum_{k=1}^N (i_k - i_k)$	0.06	0.2	0.38	0.6
Difference of absolute values sum and the differential current module	$\sum_{k=1}^N i_k - \left \sum_{k=1}^N i_k \right $	0.03	0.11	0.23	0.41
Branch maximum current	$\max_{k \in N} \{i_k\}$	0.03	0.12	0.27	0.61

However, at practical realization of the mentioned algorithms there are considerable difficulties which are caused, first, by CT cores saturation at the high values of SC currents and an aperiodic component in a primary current; secondly, at external short circuit phases discrepancy of branch currents.

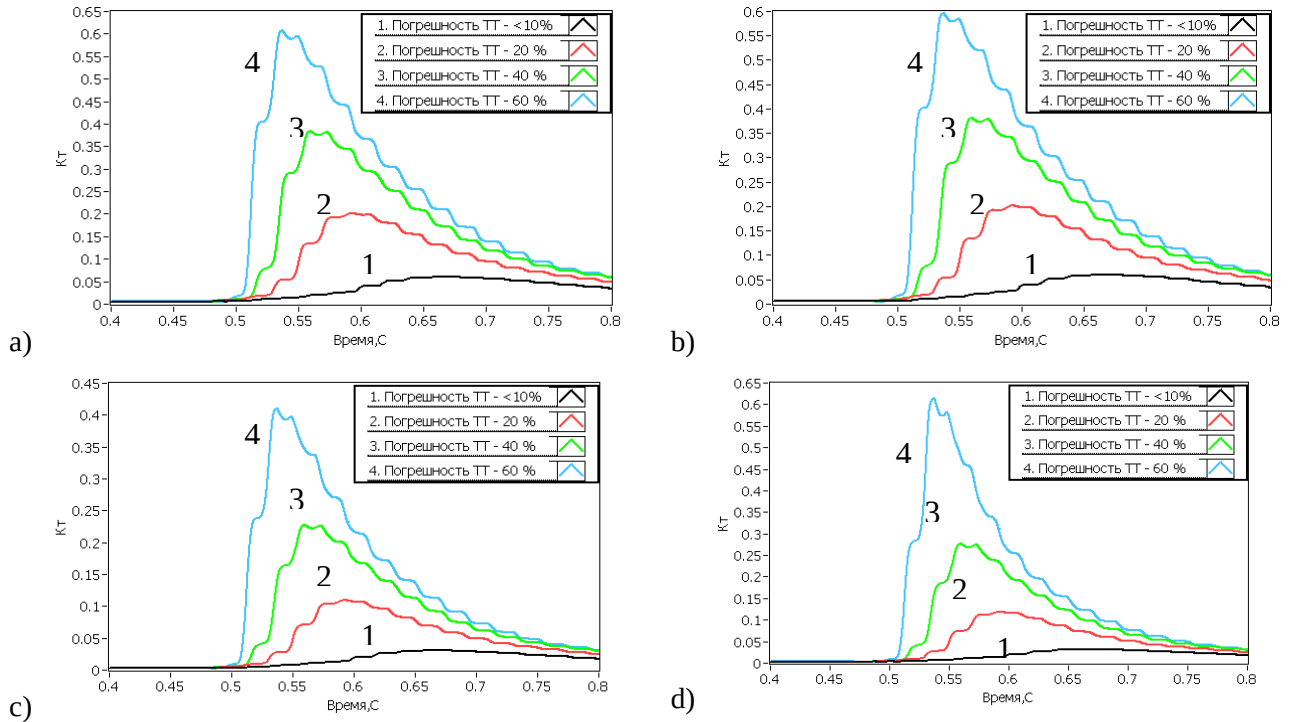


Fig. 4: Relation of a differential to bias current change at following algorithms
a) branch maximum current
b) maximum sum of positive and negative halfwaves of branch currents
c) sum of absolute all branch currents values
d) Difference of absolute values and the module of a differential current

As shown in researches [4], the most comprehensible in this respect are the bias signals generated on algorithms 1,2. The restrain signal takes place at internal short circuit at these algorithms that isn't desirable from the point of achievement of the greatest sensitivity and protection operation reliability. To a certain extent to overcome the specified contradiction algorithms with use of phase braking allow, for example

$$I_T = \sqrt{I'_1 I'_2 \cos a},$$

where

$$I'_1 = \max_{k \in N} \{ |i_k| \},$$

$$I'_2 = \sum_{k=1}^N I_k - I'_1,$$

$$a = (I'_1) \wedge (-I'_2)$$

At use of phase restraining it is necessary to take into account a methodical error of calculation current vectors at a frequency deviation from nominal and presence of an aperiodic component of a current which causes CT saturation. Partially using special digital filters allows lowering this error, which in turn leads to differential protection operation delay more than on 20 mc. Thus, completely to exclude incorrect work of the given algorithms is impossible, that leads to necessity to increase value restrain coefficient (fig. 4) or to increase calculation time, and as consequence, to sensitivity and speed decrease.

CT error in dynamic regimes is the main reason preventing further sensitivity and speed operation of transformers' differential protection increase. Undoubtedly to assert that with using true primary currents protection would have advanced characteristics. Thus the problem of renewal primary current of protection branches according to measured secondary currents is arises.

3 CT MAGNITIZATION CURRENT CALCULATION AND USING IT IN BIAS CURRENTS' FORMING ALGORYTHMES

According to the automatic control theory for restoration of the input variable incoming in a link with known transfer function $W_1(p)$, it is necessary to connect consistently a link with inverse transfer function $W_2(p)=1/W_1(p)$.

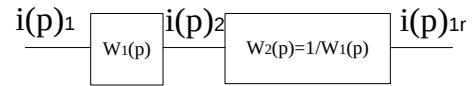


Fig. 5: Principle of using CT inverse model

Generally the transfer link 1 should consider parameters of all measuring path, including characteristics and the scheme of measuring CT, secondary switching wires resistance, secondary converters, and also ADC parameters (fig. 7). Current signals incoming on the inverse CT model input lineary proportionate to CT secondary current $i_{2A'} = i_{2A}$ when the ADC choice wright and high quality secondary converters uses with sufficient operation range.

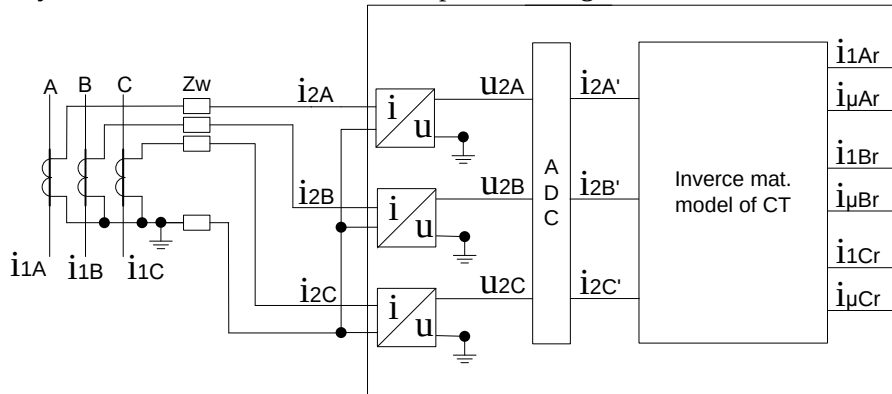


Fig 6: Primary currents restoration block diagram

Phase components method allows to execute theoretically full calculation of single-phase CT group. The greatest attention is given development of this method in works of Aleksandrov G. N, Evdokunin A.G., Popov M. G, Ragozin A.A., Shakirov M. A. As a result of CT inverse model use there is a possibility of partial primary currents correction in rate of transient. Besides, the model allows building in a new fashion protection schemes as in it directly there is a signal proportional to a

CT magnetization current, defining a differential protection unbalance current at external and internal SC.

Thus difficulties cause approximations of a ferromagnetic material magnetization curve, it is caused by necessity of taking into account the following factors: a residual induction of CT; limiting specific cycles of characteristic $H=f(B)$; magnetization characteristic frequency dependence. Some methods considering the given phenomena are presented [5]. Above mentioned causes that time of calculation of adequate mathematical model can be inadmissible great. At the same time in some practical appendices it is possible to use the simplified mathematical description of a CT.

The greatest interest represents algorithm of restraining current formation on the basis of a CT magnetizing currents geometrical difference of protection object all branch. In the algebraic form it is possible to present this way:

$$i_m = \sum_{j=1}^l i'_{\mu j} - \sum_{s=1}^m i'_{\mu s} \quad (2.)$$

where $i'_{\mu j}$ and $i'_{\mu s}$ - CT magnetizing currents according to j th and s th protection branch; l - number of branches on which currents follow in a protection zone; m - number of branches on which currents follow from a protection zone.

The differential signal at external SC is defined by the expression

$$i_\delta = (i'_{\mu I} - i'_{\mu IB}) - (i'_{\mu I} - i'_{\mu IB}) \quad (3.)$$

where $i'_{\mu I}, i'_{\mu IB}$ - reduced values of CT magnetizing currents

$i'_{\mu IK}, i'_{\mu IIB}$ -calculated values of the reduced CT magnetizing currents

Then, the bias current will be calculated by the equation

$$i_m = i'_{\mu IB} + i'_{\mu IIB} \quad (4.)$$

Differential and restrain signals at SC in a protection operative zone:

$$i_\delta = (i_{2I} + i'_{\mu IB}) + (i_{2II} + i'_{\mu IIB}) \quad (5.)$$

$$i_m = i'_{\mu IK} - i'_{\mu IIB} \quad (6.)$$

The most adverse working conditions of differential protection is characterized by saturation of one protection branch CT. Thus if to pass to rms values it is possible to write down

$$\left(\frac{I_\delta}{I_m} \right)_{\text{extern}K3} = \frac{I'_{\mu I} - I'_{\mu IK}}{I'_{\mu IK}} = \frac{I'_{\mu I} - k_\delta I'_{\mu I}}{k_\delta I'_{\mu I}}, \quad (7.)$$

$$\left(\frac{I_\delta}{I_m} \right)_{\text{intern}SC} = \frac{(I_{2I} + I'_{\mu IK})}{I'_{\mu IK}} = \frac{I_{2I} + k_\delta I'_{\mu I}}{k_\delta I'_{\mu I}} \quad (8.)$$

where $k_\delta = \frac{I'_{\mu IB}}{I'_{\mu I}}$ - coefficient of an inverse CT model accuracy

It is obvious that at use of the inverse model providing magnetization current restoration with a margin error no more of 50 %, a condition $I_m > I_\delta$ is correctly. At internal SC the condition is always satisfied and sensitivity of protection in transitive modes essentially increases, and is defined only by a constant component of a unbalance current.

As a result of the comparative analysis of various ways of formation of a restrain signal at restoration of a magnetization current with use of CT mathematical model the least is revealed desensitization protection with application of the described algorithm. It is established that in all settlement researches SC in an operative range size of a relative current of operation of differential protection to aspire to value of frequency rate of current $K3$. At external SC a settlement current of operation to be in area of negative values.

REFERENCES

- [1] Analysis of transformer failures. William H. Bartley P.E. // International association of engineering insurers 36-th annual conference, Stockgolm, 2003.
- [2] Львов М.Ю. Анализ повреждаемости силовых трансформаторов напряжением 110 кВ и выше // «Электричество». 2010, № 2. С. 27-31.
- [3] Гараева Н.Р., Медина Гарай К.Э., Попов М.Г. Разработка методики синтеза усовершенствованных математических моделей автотрансформатора.// «Изв. вузов Электромеханика», 2010, спецвыпуск «Диагностика энергооборудования ». С. 28-30.
- [4] Добродеев К.М., Курицин В.П. Дифференциальное реле для защиты трансформаторов // «Изв. Вузов. Электромеханика». 1977, № 9. С. 993-999.
- [5] Наумов В.А., Шевцов В.М. Математические модели трансформатора тока в исследованиях алгоритмов дифференциальных защит // «Электрические станции». 2003, № 3. С. 51-56.