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TRANSIENT PROCESSES IN GROUPS OF CURRENT TRANSFORMERS FOR RELAY PROTECTION

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ABSTRACT

This paper presents methods of mathematical modeling of electromagnetic processes in groups of current transformers for protection, and excluding the calculation of the electrical connection with the presentation of the main hysteresis and magnetization curve for the partial hysteresis loops. Measuring characteristics of each loads phase current transformer and their secondary circuits are specified. Results of simulation of transient process according to the proposed way causes significantly increasing of the effectiveness in solving tasks such as choosing or changing of phase current transformer, choosing of operation parameters for relay protection.

KEYWORDS: group of current transformers, electromagnetic transients, load asymmetry, relay protection.

INTRODUCTION

Development of technological progress constantly increases requirements for relay protection and emergency automatics of power systems (such as speed, sensitivity and selectivity). It causes to obtain more detailed and accurate information about the type and peculiarities of electromagnetic processes in the common measuring devices in electric networks. Particularly, it is a current in steady and transient operation modes such as electromagnetic high current transformers (CTs) and their secondary circuits. The information needs to evaluate the impact of these processes on the functioning of relay protection and automation (PRA). It helps to choose their operation parameters, substantiating of the correct choice of a phase CT in single or 3-phase group to replace the broken CT and to solve numerical PRA practical tasks. For receiving these information, there are different types of modelling; the most common are physical [1-5] and mathematical models [4, 6-10]. In power nets, the real experimental studies of CT in operation are impossible [11]. Moreover, studies on test benches and in the laboratory are complexity and require playback modes of power nets (steady and especially transition modes). As a result, modelling is rather complex and economically costly.

Nowadays, many models for calculation of transient processes (TPs) in a single CT and dependence between input parameters of schemes and the magnetization current of magnetic investigate in details in [12-17]. However, the accuracy of CT is standardized by NSO 7746-2001 [18, 19].

Structurally CT is a single-phase device. So for a complete description of the electrical parameters of controlled 3-phase accession in a place of protection settings (depending on the method of connection of neutral lines), CTs are installed in all three phase line (networks with a voltage of 110 kV and above), or only in two phases line (networks with a voltage of 35 kV). Secondary windings of phase CTs and electric circuits for currents measuring of RZA connect into the circuit. The configuration and the number of elements is determined by the needs of the protection [20-22].

Due to the presence in the circuits of CTs group a large number of non-linear elements, a research of TP tasks and identification of influential factors is a very important target. Negotiation of possible differences between phases of CT and certain features of loads in secondary windings leads to significant errors [23-27].

Note. Variety of different types of CT manufacturers and their specifications causes needs a scientific justification and numerical practical cases of operating current circuits PRA – truthful calculation of the CT, through:
- consideration of the single CT,
- impact of differences in the characteristics of individual phases of CTs to a transition process,

- features of setting of PRA inserts, taking into account differences between characteristics and load of CTs in the group.

In modern simulations of practical tasks, a scheme of circuit connection of CTs is performed by introducing amendments to the definition of a load in CT secondary circuit [20, 28]. TP in phases CTs is calculated separately and the values of secondary current or magnetizing currents of CTs cores are compared and analysed. According to the specified approach, the impact on the individual CTs to the electric circuit is not considered at all.

In papers [12, 24-27, 29-32], such tasks have solved, but with the adoption of a several simplifications:
- all phase CTs are equal,
- loads in secondary circuits of the phase CTs are equal and mostly active or inductive-active,
- during TP there is no any residual induction in the magnetic,
- the process of phase CT saturation is known in advance.

Note. In these groups simulation, the magnetization characteristics (MChs) of CT are presented by the magnetization curves (MCs) in the simplest ways (straight and rectangular MChs) [23-25]. As a result, these methods are more suitable for analyses, than modern practical calculations.

The calculation for the 3-phase measuring complex is given in the paper [33]. However, specified method requires adaptation to the protective features of CTs and additional research. Comparison of experimentally obtained oscillograms of TPs in the CTs group with the relevant calculations indicates a need to study the complete scheme [25], however, technical limits for solving this problem do not clearly justify.

SCHEME OF CT AND RELAYS CONNECTION. MAIN PRINCIPLES

The development of modern electrical systems is characterized by increasing the time constant of the system, reducing of the time relay operation and, therefore, disabling emergency operation time. This causes the growth of an impact of TPs to the operation of CT in the PRA. As the effect of TPs, it is possible slowdown and false triggering of PRA [2, 34]. For development and practical application of CTs, it should be considered a particular need to ensure the accuracy of their operation during stainable modes and also in transient processes.

A common feature of all errors for protective CTs is their dependence in time. Depending on the type of protection and specific conditions of the study, the maximum error of the estimated value determines during the full period of the TP or during operating frequency with accounting of calculated period. For some high-speed devices of PRA, it should be determined the time over which the CT’s error is not exceed allowed values.

Above given factors, the requirements of a model for CTs group are formulated as follows:

1. Necessity of consideration of availability for electrical communications between secondary windings of phase CT in accordance to the connection scheme.
2. Depicting of a neutral wire by its full load.
3. Models of scheme for phase circuits of CT correspond to their magnetic design features.
4. Loads of separate phases of CT are represented by active and reactive loads and could be differ from each other (with asymmetry).
5. TP calculation is performed according to the time of PRA operation.

Since there is a number of research methodologies for a single CT, then a comparison uses a mathematical model in which the phase CT is represented by a family of hysteresis loops, and its secondary load is selected in accordance with the connection groups (Table) [28].

Load of a secondary winding of CT consists of a series-connected resistances: relays z_{relay}, devices z_{dev}, cores of control cable z_{cable} and transition resistance z_{trans} at the point of contact connection and in general is:

$$z_{load} = z_{relay} + z_{dev} + z_{cable} + z_{trans}.$$

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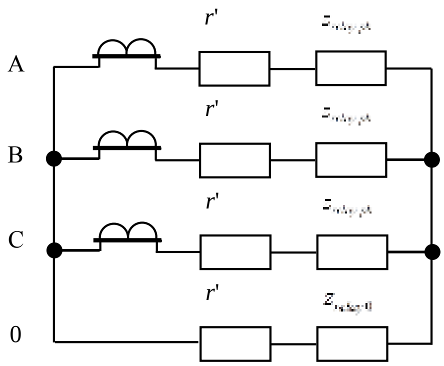
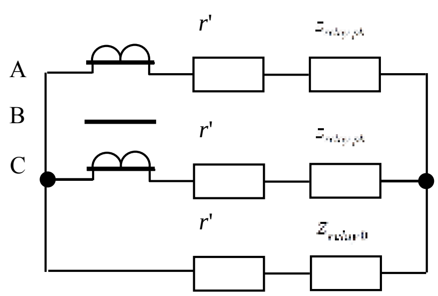
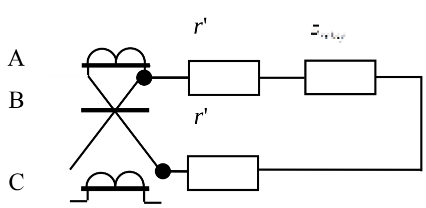
Table - Determining of the load of secondary windings according to a group of CT connection

Scheme of CT and relays connection	**Type of short circuits (SCs)**	**Formula to determine the load at the terminals of secondary windings**
 Complete Y	3-phase and 2-phase	$z_{load} = r' + z_{relay} + r_{trans}$
	Single-phase	$z_{load} = 2r' + z_{relay\ ph} + z_{relay0} + r_{trans}$
 Incomplete (part) Y	3-phase	$z_{load} = \sqrt{3}r' + z_{relay\ ph} + z_{relay0} + r_{trans}$
	2-phase AB or BC	$z_{load} = 2r' + z_{relay\ ph} + z_{relay0} + r_{trans}$
	2-phase for CT Y/Δ-11	$z_{load} = 3r' + z_{relay\ ph} + z_{relay0} + r_{trans}$
 Difference of current phase A-C	3-phase	$z_{load} = \sqrt{3}(2r' + z_{relay}) + r_{trans}$
	2-phase AC	$z_{load} = 4r' + 2z_{relay} + r_{trans}$
	2-phase AB or BC	$z_{load} = 2r' + z_{relay} + r_{trans}$
	3-phase or 2-phase, 3-phase for CT Y/Δ-11	$z_{load} = 3r' + 3z_{relay} + r_{trans}$

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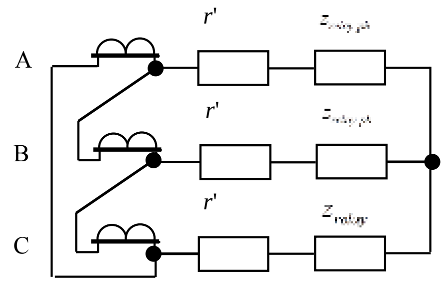
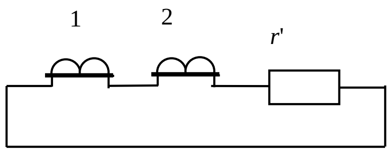
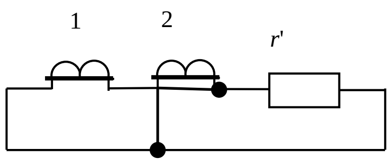
Scheme of CT and relays connection	Type of short circuits (SCs)	Formula to determine the load at the terminals of secondary windings
 Triangle	Single-phase	$z_{load} = 2r' + 2z_{relay} + r_{trans}$
 Serial connection of secondary windings of CTs		$z'_{load} = 0,5z_{load}$ where $z_{load} = 2r' + z_{relay} + r_{trans}$ At the same characteristics CTs 1 and 2
 Parallel connection of secondary windings of CTs		$z'_{load} = 2z_{load\,estim}$ where $z_{load} = 2r' + z_{relay} + r_{trans}$ At the same characteristics of CTs 1 and 2

In Table, for a calculating of the load depending on the CT circuit connection, the following abbreviations use:
r_{dev} is resistance of devices;
r_{trans} is resistance of transition contacts;
z_{load} is estimated resistance of the load;
$z_{relay\,ph}$ and $z_{relay\,0}$ is resistance of the relay in the phase and neutral wire.
The value r_{trans} is set up to 0.1 ohms in all cases.

For simplified calculation it is recommended to use arithmetic, but not geometric adding of full and active resistance. For comparison let use the largest load of CT or, in other words, the calculation with most downloaded CT - the worst case.

For taking into account the load of the CT, it should be considered the following. In practice, there are many old electromechanical and microelectronic relays. The main characteristics of microprocessor protection are much higher than microelectronic ones, and much more than electro mechanical ones. The power consumption of the CT is fixed at 0,1-0,5 BA, a hardware error is 2.5%, the rate of return equals to 0,96-0,97.

Operating experience of electromechanical devices of PRA indicates the total service life of about 25 years, it is more than 2 times larger than an average period, set in accordance with technical requirements. For example,the lifetime of magneto electric relay is limited to 6 years, and microelectronic one is up to 10. Similarly, restrictions exist for the installation of wires, contactors, cables. In turn, the technical documentation for PRA devices on a microelectronic and a digital base with the average duration of a timeline specified as 12 years. Average lifetime of CT is about 25 years and can significantly increase.

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In operation, CTs, PRA, wires, contactors, control cables have a different lifetime; however, the replacement is not complex. Each connection is unique. So typical calculations are not suited to such tasks.

Let analyse in detail the connection Y. In this case, the neutral point of PRA devices connects with the CT neutral wire, it insures the availability of common neutral reverse wire. In such way, two wires in any cable are saved.

Thus, in a symmetrical 3-phase mode, secondary current for every CT passes only through their own resistance phase, because the current in the neutral wire is zero. During 2-phase SC, two CTs transmit current, flowing in two phases, that is similar to the 3-phase SC and the current in the neutral wire is also absent. Formulas are given in Table.

Calculated values of the load could be differ from the actual one; so it should determine empirically. In general, the load of CT secondary winding is defined as:

$$z_{load} = \frac{U_2}{I_2}.$$

The voltage at the terminals of the secondary winding of CTs U_2 is voltage that drops in the connected load:

$$U_2 = I_2(z_{relay} + z_{cab} + z_{trans}).$$

where I_2 is a current of the CT secondary winding.
Therefore, it is necessary to determine z with the prior formula to calculate U_2 with the actual throwing of currents in the secondary circuits at given circuit connections and secondary windings in the estimated type of SC.
Resistance of control cables and wires:

$$r' = \frac{l}{\gamma S}$$

where l is a cable length,
γ is a conductivity equal to 57 ohms/m for copper and 34 ohm/m for Al,
S is a section of conductor cable or wire.
Impedance of relay and device calculates with known level of consumption:

$$z_{relay} = \frac{S_{relay}}{I_{relay}^2},$$

where S_{relay} is a power of relays and devices;
I_{relay} is a current of the consumption.

Let perform the calculations of comparing simulation results of TP in CTs group. On the one hand, one takes into account the availability of electrical connection between secondary circles of CTs, on the other hand it is in separate single CT, which secondary loads are calculated according to Table.

EVALUATION OF THE IMPACT OF CONNECTION OF CTS CIRCUIT

Symmetrical 3-phase SC is the most difficult in terms of calculation and analysis. In this case, there is a complete calculation for individual phases.

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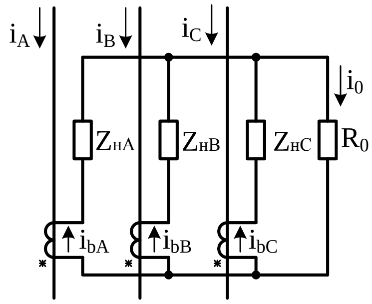
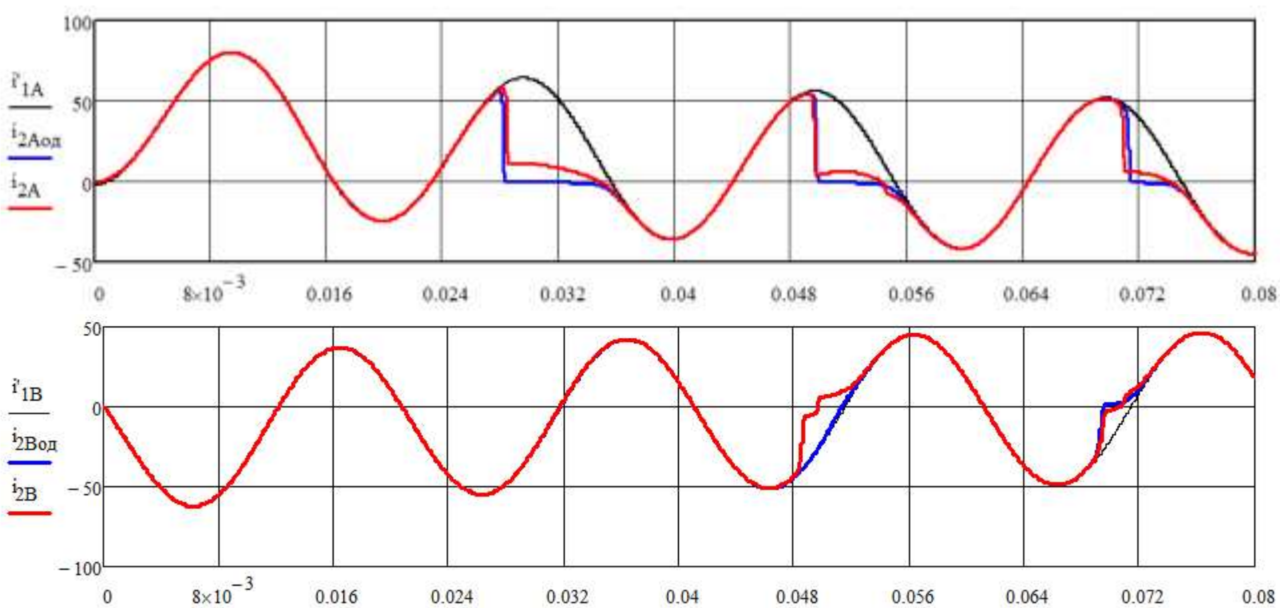


Figure 1 - Scheme of connection "Y-Y"

Research makes for the group of CT and the scheme is shown in Fig. 1. Established CT-110 II U1 (oil CTs for outdoor installation, pollution degree according to NSO 9920-89 (II), nominal voltage (110 kV) and climate design U1) with nameplate manufacturer, $I_{1\ load}$ = 600 A, $I_{2\ load}$ = 5 A, w_2 = 120, S = 14,56 cm^2, l = 1,1 m, $r_{int\ (5A)}$ = 0.275 ohms.
The basis of the proposed mathematical model for a 3-phase group is three equations for single CTs. Before modelling of TP, the initial conditions should be formulated. In normal operation, protective CT works with small values of magnetic induction, which is usually neglected [1]. For the case when PRA is equipped with an automatic recloser, residual magnetic induction of cores can be up to 60% of the maximum values (its consideration is necessary in the calculations). However, in such systems, according to the paper [30], based on technical and economic conditions, CT is set with disconnected magnetic Y type, where the residual induction is absent. Preliminary calculation of initial conditions shows that the induction in a separate phase of CTs until a SC within 0,12Tl. So for this task, residual magnetisation is negligible.

The calculation of the 3-phase SC fulfil in the conditions of uniformity of characteristics of phase CTs and their full loads of circles 0.92 ohm, resistance of a neutral wire is 0.2 ohms.

The results of simulation for secondary currents of group "Y-Y" of CT are shown in Fig. 2.



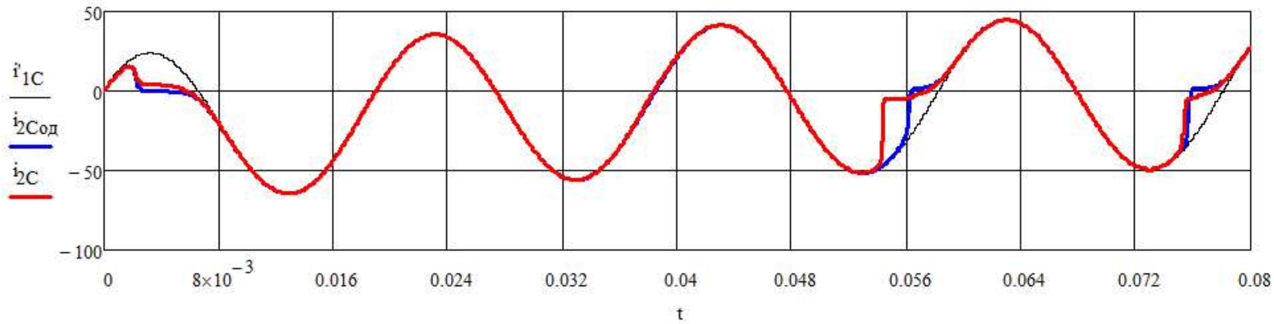


Figure 2 - CT secondary current in phase CTs during 3-phase SC

(i'_{1A}, i'_{1B}, i'_{1C} are instant values of primary current of phases;
$i_{2Aод}$, $i_{2Bод}$, $i_{2Cод}$ are instantaneous values of secondary currents of circuits phase CTs that are calculated excluding telecommunications for a group of connection;

i_{2A}, i_{2B}, i_{2C} are instantaneous currents of secondary circuits phase CTs).
In general, during 3-phase SC a group of connection "Y-Y" with a saturation of one CT decreases the inductive resistance of circuit magnetization. CTs in the neighbouring phases are not saturated and their secondary currents are distributed between phase of saturated CT and a neutral wire leadership under the rules of "alien shoulder”. The process of the current supply for the secondary winding is in the zone of saturation. During the output CT from the saturation, magnetization inductive reactance increases, i.e. CTs of the neighbouring phases stop to feed indicated phase. Then currents supply is restored, but the process begins from the phase with saturation. When one of CTs is saturated, the resistance of a neutral wire is shunting and thereby facilitates operation for neighbouring phases.

Analysis of Fig. 2 shows that the calculation process of the CT to the saturation of phase A, secondary current i_{2Aod} defines by a single CT according to the recommendations of Table does not lead to a worth results of the calculation process. After CT saturation, without taking into account the electrical connections leads to errors and, consequently, increases the possibility of an incorrect choice of PRA inserts (e.g., in the 3rd and 4th periods, instant full circuit current i_{2A} takes smaller values for the relevant i_{2Aod}, that the current error is calculated incorrectly towards its reduction). Similar processes occur in other phases.

3-phase SC is symmetrical and losses are only available in magnetic cores of phase CTs and currents trigger in the neutral wire (Fig. 3).

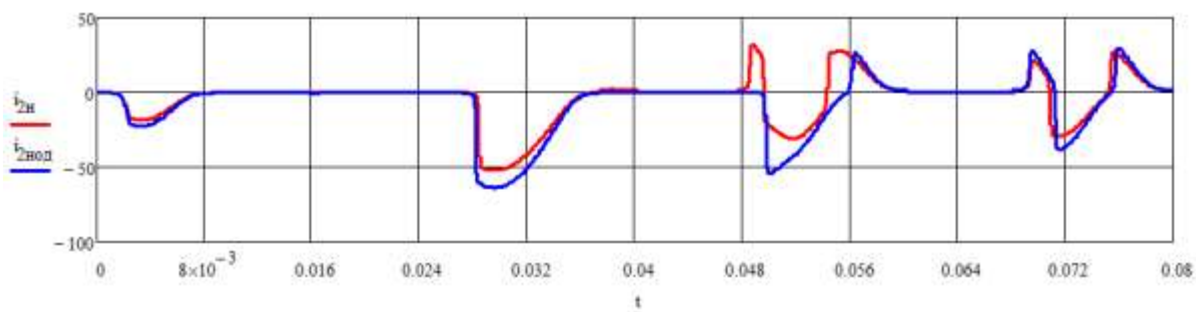


Figure 3 - The currents in the neutral wire for the circuit connection "Y-Y"

$i_{2н}$ and $i_{2нод}$ are instantaneous currents in the neutral wire with and without the telecommunications within a group.
In the calculation of electrical connections TP should be taken into account after saturation in any of the phase CT. Neutral wire has a positive influence on the currents in phase CTs during interphase SC due to the appearance of the current phase in it. Such current can be estimated by the effect of protection as wrong zero sequence signal, whose intensity increases with decreasing as the load of a neutral wire.

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According to the paper [24], it is recommended to increase r_0 to values when the load does not cause early saturation of CT for modes, where single-phase SC is not a determining factor (useful for differential-phase protection).

To investigate the possible errors of underestimation of the group connection hold a similar simulation for 3-phase SC scheme "part-Y", which is presented in Fig. 4; the results present in Fig. 5.

In this case, according to Table, the loading phase through a simplified calculation of single CTs is assumed to be 1.06 ohms.

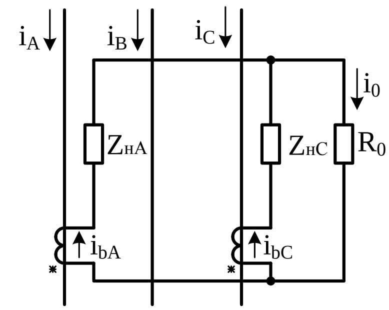


Figure 4 - Scheme of connection "part-Y"

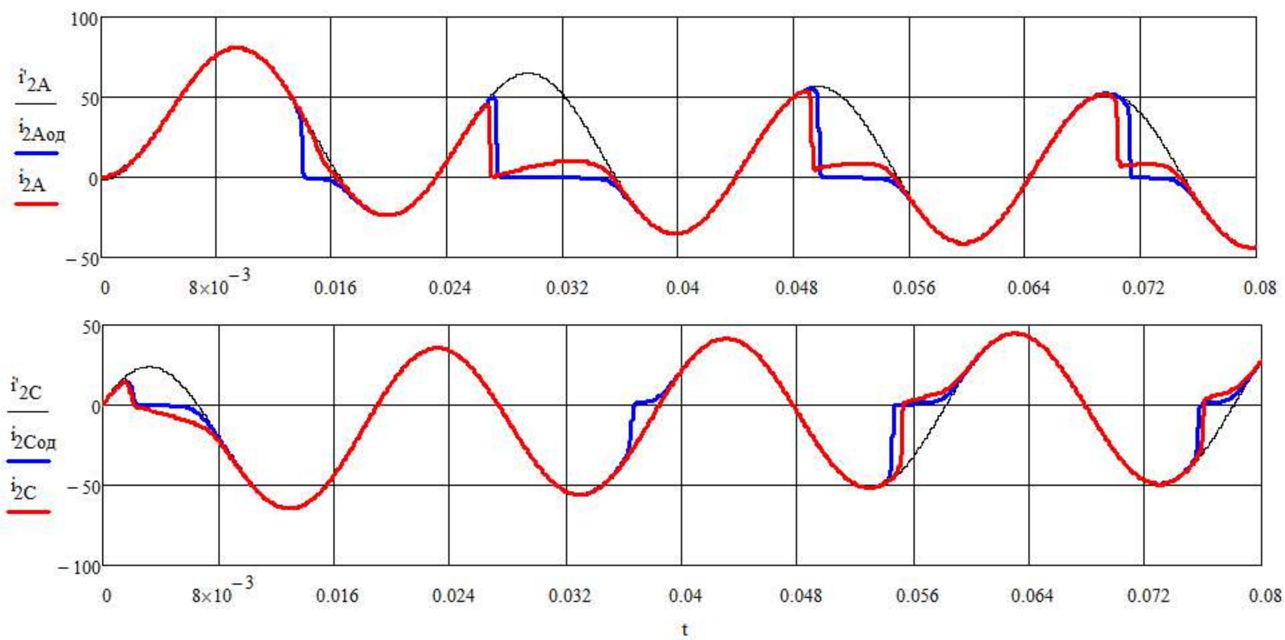


Figure 5 – TP in a group of CT with connection scheme "part-Y"

The simulation results of TP in the CTs group with a connection scheme "part-Y" indicate a possible simulation of the CTs group by the blending processes in the individual phases of CT. It is possible for a calculation until a saturation one of CTs within the group. When one of the phase CT is saturated, currents in the secondary circuits of the CT load can be significantly differ from the calculated one with simplified models, due to increase or decrease the time out of the state of saturation phase CT. In other words, for correct account of the load from neutral wire is possible just for a calculation of the full circuit connection of CTs and their secondary circuits.

Presented calculations of TPs in the current circuits of relay protection indicate a need to have a topology of connection of CTs groups in terms of simulation for 2- and 3-phase SC. A special case of single-phase SC: currents in the neighbouring phase CTs are insignificant and do not influence to the overall impact of the scheme.

ESTIMATION OF THE IMPACT OF REPRESENTATION OF MAGNETIC CORES OF CTS CHARACTERISTICS DURING TP IN THE RELAY CURRENT CIRCLES

In general, characteristics of the magnetic core in the calculation of TP are represented in the form of the MC, marginal hysteresis loop or a family of partial loops [35]. Influence of representation of magnetic cores show characteristics in Fig. 6. For clarity, calculation results of 3-phase SC present as magnetization currents of cores for phase CT.

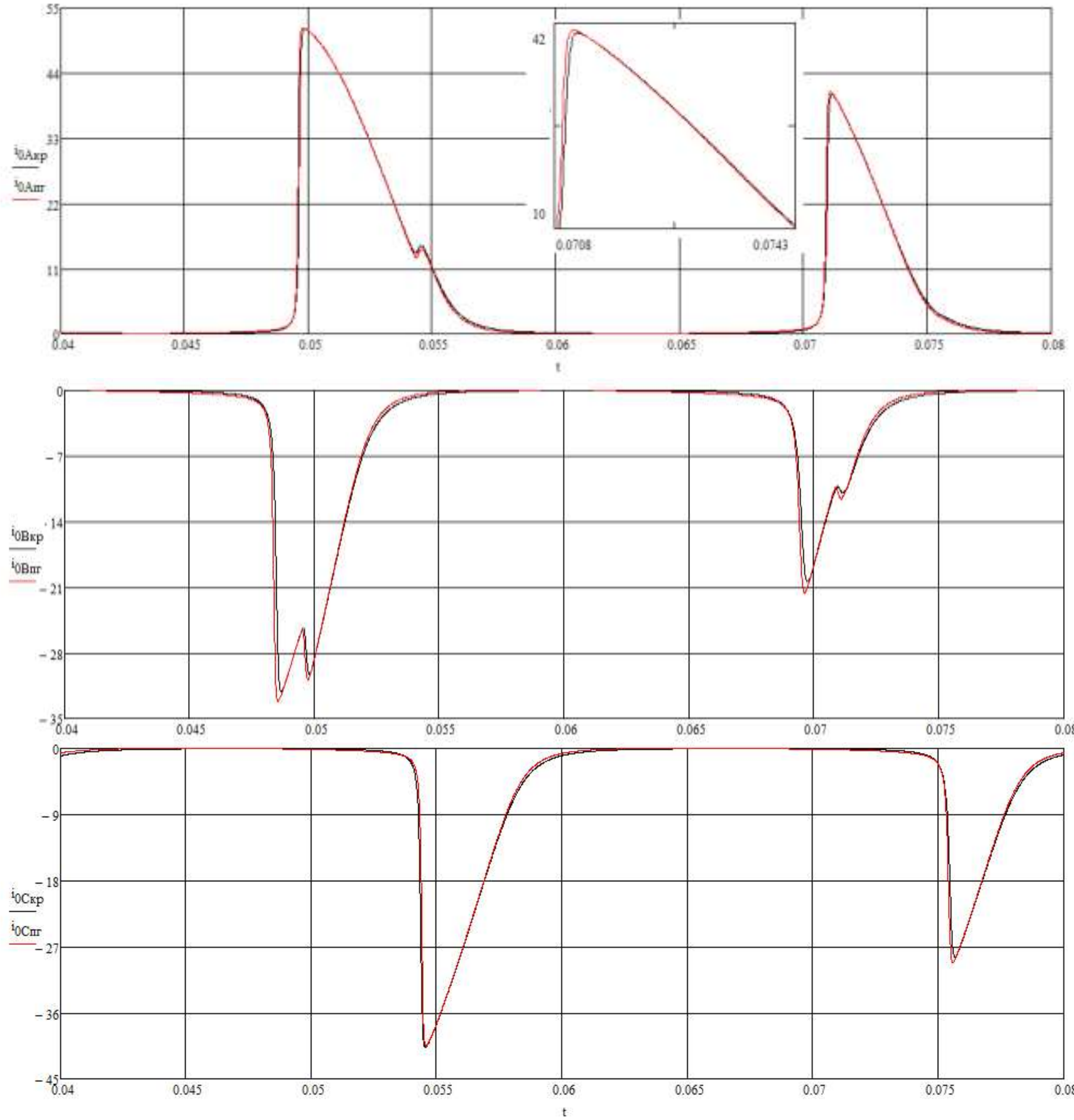


Figure 6 - TP in the CT for a modelling at the branch of the main MC and partial curves ($i_{0Aкр}$, $i_{0Bкр}$, $i_{0Cкр}$ are magnetizing currents of cores for phase CT with the main MC; $i_{0Aпг}$, $i_{0Bпг}$, $i_{0Cпг}$ are magnetizing currents of cores for phase CT with the hysteresis)

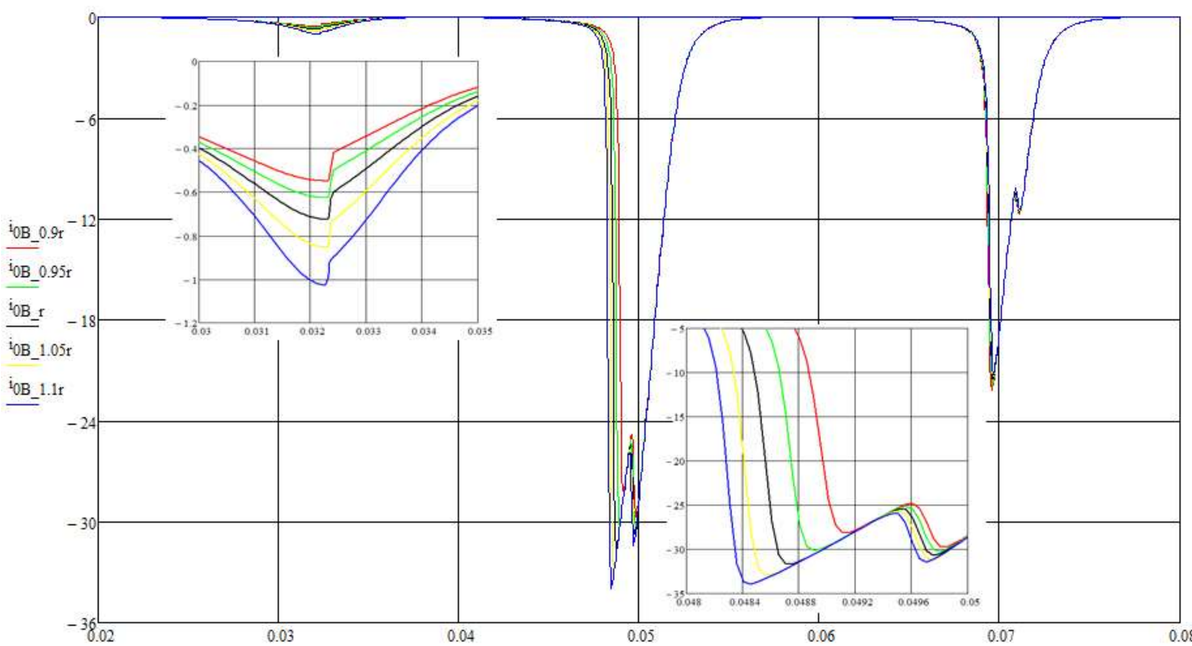
Analysis of TP in CTs group is presented in Fig. 6. The choice of calculation model of CT should be done with the initial conditions - namely, the process of considering the saturation of magnetic cores of transformers. Thus, a deep saturation of one CT magnetic in the phases (in this case C), the error of ignoring hysteresis losses may reach 10%, which corresponds to the conclusions in the paper [4]. TP in the magnetic core is calculated after MC, despite a few influence of reversal magnetisation on the core after partial curves for currents of CT secondary circuits. Condition of CTs group is completely determined only instantaneous state of the phase CTs. So one can conclude that the correct calculations for the CTs group are possible by models with the phenomenon of hysteresis.

Analysis of simulated values shows the existing relationship between "weak" and "strong" CTs. In general calculation of a scheme of the CT with worth performance does not lead to errors of CT choosing for PRA. Calculation of the scheme without "strong" CT leads to significantly overestimated current and values of angular error in the 1st and 2nd period relative to phase A. So, to setting the speed protection, taking into account differences in MChs is a prior task. Operation of CTs with different MChs should be estimated after calculations of TPs, and before the choice of "stronger" transformer. In practice, it may not be effective. Therefore, accuracy and simplicity presentation of CT MChs is the main question.

PHASE UNBALANCE OF CT LOAD IN THE CALCULATION OF TRANSIENT PROCESSES

Load of secondary circuit of CT consists of connectors, cables and resistance of PRA. The transition to microprocessor PRA causes a sharp decreasing of resistance. Since the cable length of accession CT-PRA on the high voltage substations is a significant, there is a large resistance. Under these conditions, each phase CTs have its own loads differ from other. In some cases, the difference can reach 10%.

Fig. 7 shows the instantaneous values of the magnetizing current of phases with unbalance of active load in phase A and the magnitude of -10 to + 10% of the initial value (0.9, 0.95 ... 1.1).



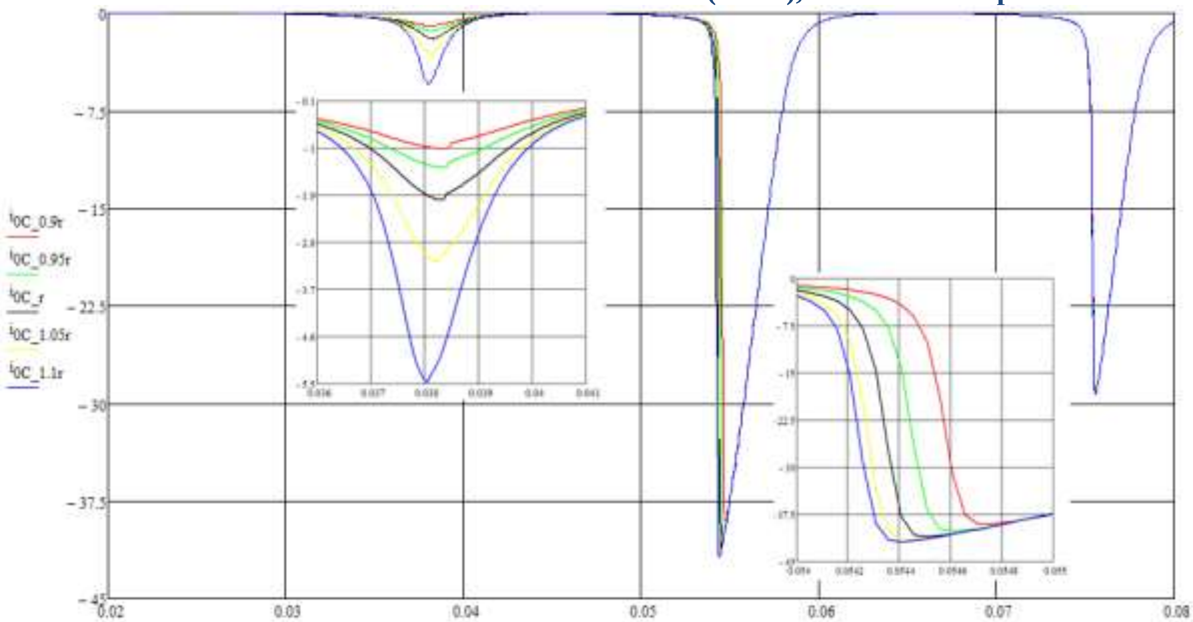
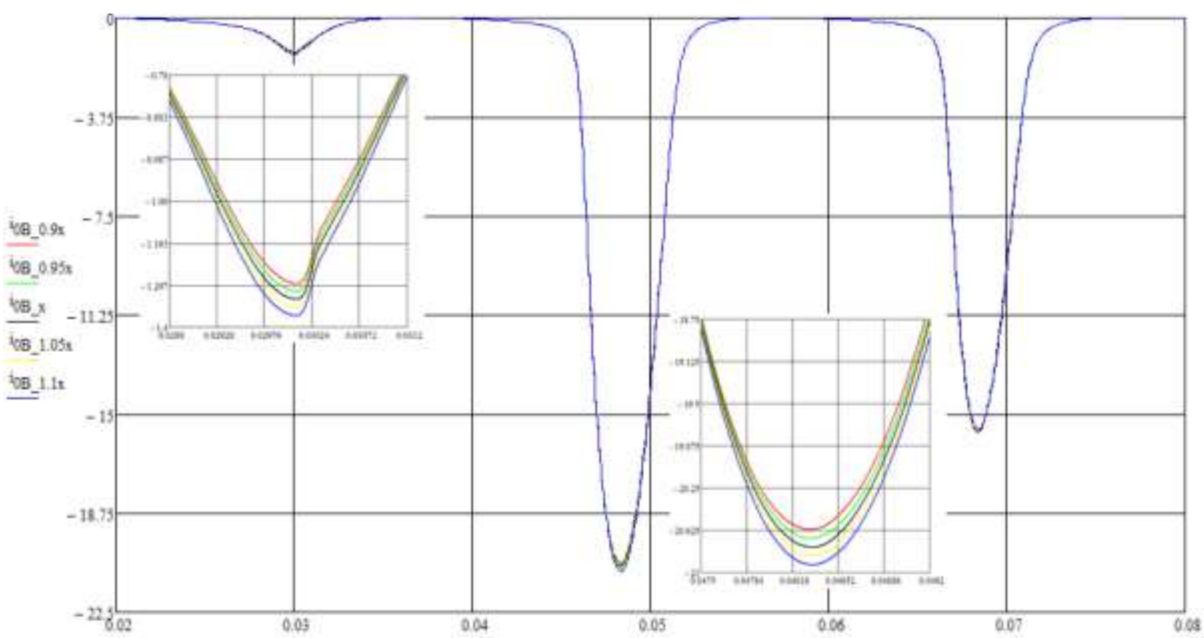


Figure 7 - Magnetization current of phases B and C relative to change of the active load of phase A

The presence of the CT within a group with a smaller load has a positive impact on the TP in the neighbouring phases. Impact of differences of loads of another phase is not appear obviously (error is up to 2.5%). For calculations that require high accuracy or estimations of inserts for microprocessor protection, such consideration is obligatory; for other possible cases it can be neglected.

The error of ignoring of various loading in phases is determined by the ratio of loads in phases to a resistance in a neutral wire. In a cases, that resistances of neutral wire are much smaller in comparing with phases and a relatively small difference of loads in phases in comparing to each other, there is no necessarity to do these calculations.



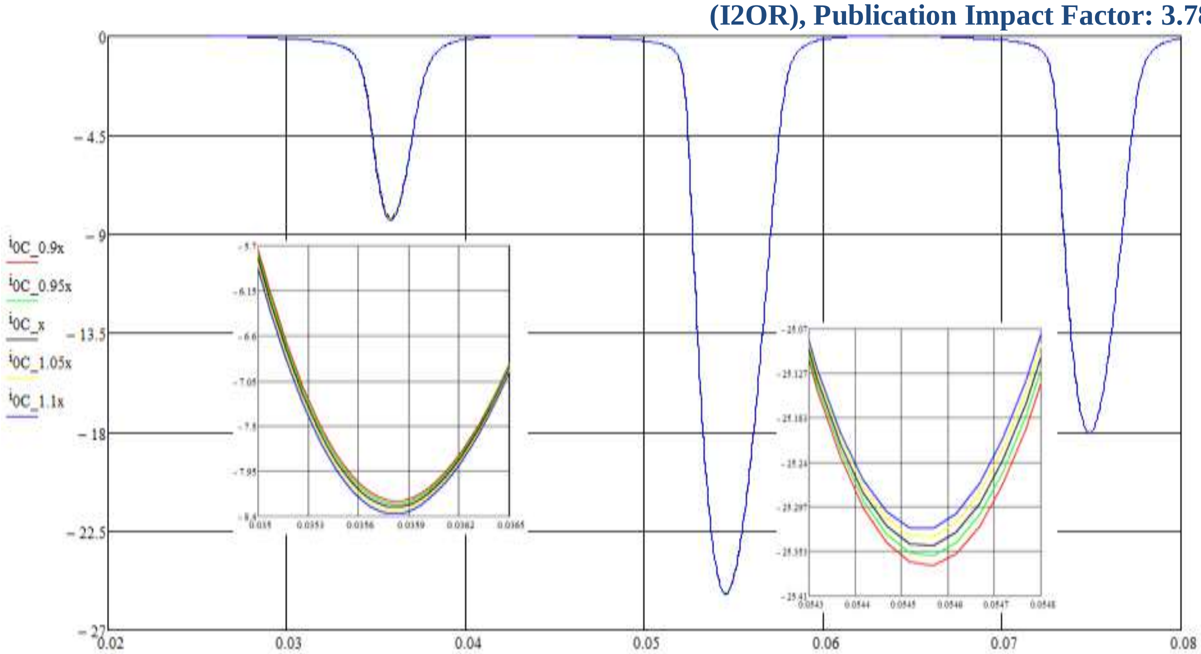


Figure 8 - Magnetization currents of phases B and C relative to changes of inductive load of phase A

The simulation results show that the change in inductive resistance within ± 10% of its nominal value have the same effect as changing of a load in a phase. The results are not almost affected on the simulation. So for the cases without a symmetry in phases, the load is neglect advisable.

TRANSIENTS PROCESSES IN THE CTS GROUP WITH DIFFERENT MCHS

In operation CT, the core's MCh deteriorates over time. Its parameters depend on many factors, including the number of SC in the phase. During replacing of the broken CT or the performance of service, in a phase CT set and its characteristics are differ from others in the group.

Operation shows that on the one hand, plants deliberately understate the CT's MChs for the purposes of the guaranteed limit errors. On the other hand, specific of manufacturing, installation, operation may not significantly influence to performance.

Fig. 9 shows the instantaneous magnetizing currents in phases, during asymmetry in a circle with changing of MC induction on the value of -10 - + 10% of the initial value (0.9, 0.95 ... 1.1).

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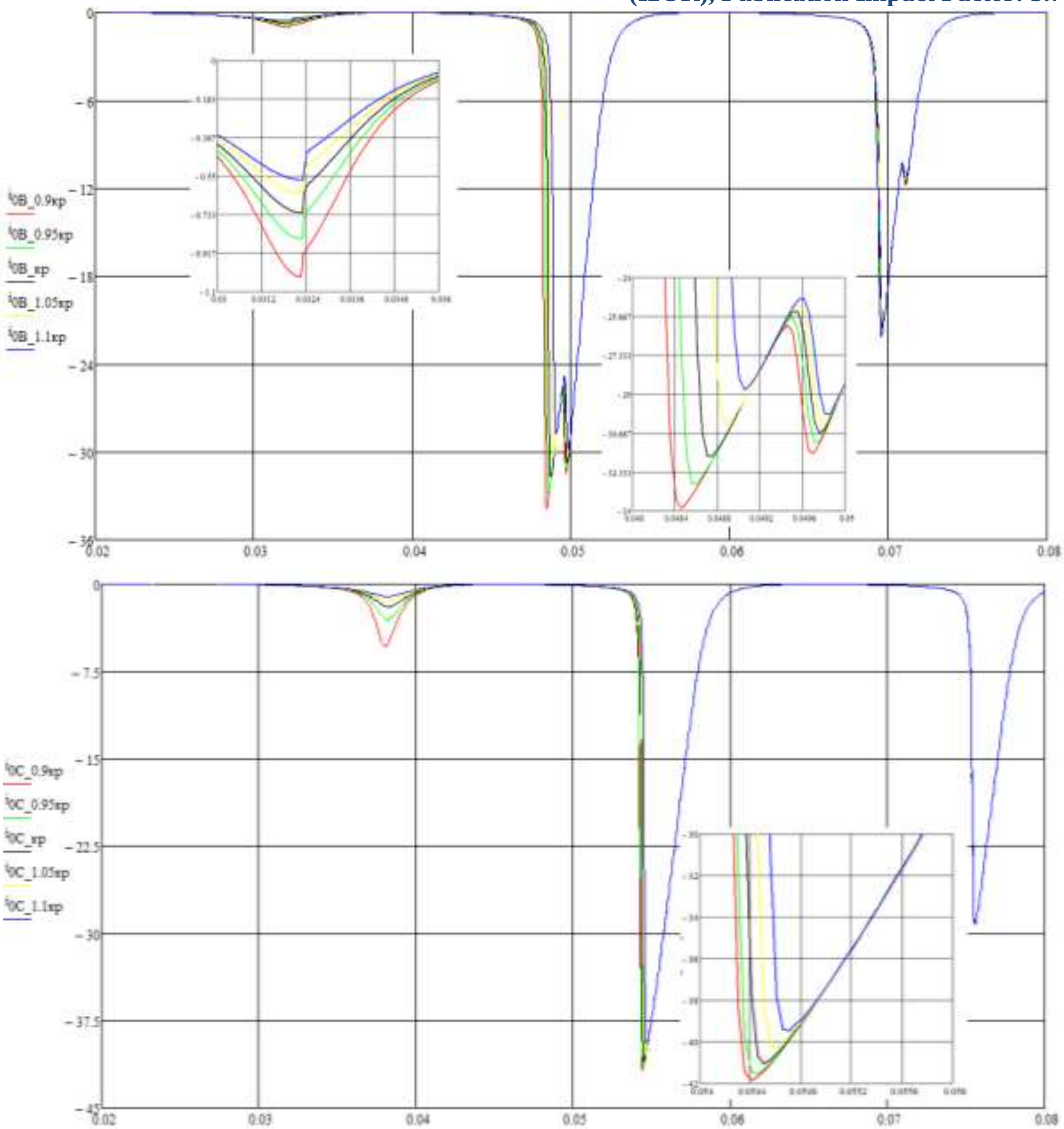

Figure 9 - Magnetization currents in phases B and C relative to change of CT MCh in phase A

The results of the research indicate that in generally the CT with the "best" MCh (intensity corresponds to induction value) has a positive effect on the TPs in neighbouring phases. The effect of the MCh in a phase of CT actually duplicates the effect of different loads in phase CTs, but the contents are opposite.

CONCLUSION

In this paper shown that TP in a single CT determines increasingly by the parameters of the CT and its load in the secondary circuit. With the saturation of one CT, decreases the inductive resistance of a magnetization circuit, while in neighbouring phases time of CT saturation is not completed; and their secondary currents are distributed between phase of saturated CT and neutral wire according to the rules of "alien shoulder." During CT saturation, resistance of neutral wire is shunting and thereby operation for neighbouring phases is simplified. Premature saturation of phase

CT, which can be caused as the increasing load of the secondary circuit, and deterioration of the MChs, lead to a simultaneous increase of magnetization current in a saturated phase and reduction of magnetization current in unsaturated phases.

Considering the reversal magnetisation process in the core after a hysteresis model for calculation of TPs in the CTs group for practical calculations is not recommended. Because the accuracy is not very significant increases with increasing quantity of calculations. Inductive load of the secondary circuit of the CTs group calculates after the average value, because asymmetry is almost without error. The difference between MChs of high voltage CTs and active load of secondary circuits is used for the TP calculation, where main criterion is an accuracy. Simultaneous without all these factors will increase the error of calculations significantly.

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