Experimental obtaining characteristics of current transformers for developing their models and determining the time of saturation of the magnetic circuit

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Abstract. Electromagnetic current transformers (CT) are subject to saturation and residual magnetization of a magnetic circuit. This phenomenon has an impact on the operation of devices of commercial accounting of electric energy and relay protection and automatics (RPA). Saturation of the current transformer’s magnetic core can lead to emergency situations due to incorrect operation of the protections and excessive disconnection of the protected connections. At the moment, Russian norms do not regulate the work in transient modes, including short circuits with an aperiodic current component. The Ivanovo State Power Engineering University (ISPUE) conducts research on the topic of determining the time to saturation of CT at short circuit. The purpose of the work was to develop an algorithm for monitoring saturation and determining the time to saturation of the CT magnetic core, in order to ensure the correct operation of the RPA in all modes. The article is devoted to the method of construction and research of mathematical models of CT for calculating the time to saturation. The general structure of the algorithm for determining the time to saturation is presented.

1. Introduction

During operation, the conversion error of current transformers (CT) may not meet the requirements of the declared accuracy class due to distortion of the shape of the current curve due to the influence of the residual magnetization of the magnetic circuit, which may appear after disconnecting the short circuit. This phenomenon has a significant impact both on the operation of the commercial electricity metering system and on the operation of relay protection and automation devices (RPA). Accordingly, incorrect accounting of electricity supplied or consumed may be maintained for a long time. However, more significant commercial and operational implications happen during the wrong action of relay protection and automation.

The issue of CT saturation and modelling of transients in secondary CT chains has been given close attention in the USSR and the world since 1960-80s. A large number of works by such specialists as I. M. Sirota, A. D. Drozdov, V. E. Kazansky, L. V. Baginsky, V. I. Novash and their students were devoted to the problems of CT operation in transient short-circuit modes [1]. Measures were developed to eliminate saturation of the magnetic circuit, including the use of CT with a voltage of 750 kV and 1150 kV with a non-magnetic gap, and methods for calculating loads on the CT were developed [2]. To eliminate the influence of CT saturation, CT with new accuracy classes were used in foreign practice. RPA algorithms were developed and applied everywhere, implementing the correct operation of protection with a speed of about half a period of industrial frequency in conditions of deep CT saturation.
However, the results of the theory of CT operation in transient modes are not taken into account in existing domestic standards on CT. Several major accidents, including those in 2018 in the Crimea and 2014 at the Rostov nuclear power plant, caused the release of a new series of standards for measuring CT and a number of works on the topic of CT saturation, designed to ensure the correct operation of the RPA connected to electromagnetic CT, at short circuit, including when there is an aperiodic component of the current [3, 4].

For a number of large power facilities in the Russian Federation, it has become mandatory to monitor the state of the CT and estimate the time to saturation of the CT at short circuit. In accordance with the requirement of JSC "System Operator of the Unified Electric Power System" ("SO UEPS"), it is necessary to calculate the time to saturation of the CT at approximately 100 power facilities by 31.12.2020.

Therefore, it is important to develop and study an algorithm for determining the time to saturation of the current transformer magnetic core to assess the correct operation of RPA devices and current transformers in transient modes. This paper presents the results of the development and verification of CT simulation models designed to work out algorithms and principles for determining the time to saturation, as well as the calculation of the time to saturation of CT type TZLM, available in the laboratory of the Ivanovo State Power University.

2. Mathematical models of CTs
For the development and verification of models, a CT of the TZLM type was selected (figure 1). The TZLM Passport data required for modelling are summarized in table 1.

![CT of type TZLM](image)

**Figure 1.** CT of type TZLM.

| Type of magnetic core steel | Length of the average power line of the magnetic circuit L, cm | The cross-sectional area of the core S, cm² | The number of turns of the secondary winding |
|---------------------------|---------------------------------------------------------------|------------------------------------------|-------------------------------------------|
| steel                     | 3411                                                          | 33.9                                      | 7.2                                       | 25                                        |

CT models were developed in the RSCAD program environment of the RTDS hardware and software complex, which has earned its trust and has been repeatedly tested for the purpose of modelling objects and modes of electric power systems and RPA devices.

In the course of the work, three CT models were developed and studied (figures 2 – 4):

1. CT simulation model based on Faraday's electromagnetic induction equations. The main ratios for calculating the output value (EMF of the secondary CT winding) are shown below (1) [5]:

\[
\text{EMF} = N \cdot \frac{\text{d}B}{\text{d}t}
\]
\[ F_{\text{sum}} = I_1 \cdot w_1 - I_2 \cdot w_2, \quad H = \frac{F_{\text{sum}}}{L}, \quad H \rightarrow B, \]

\[ \Phi = B \cdot S, \quad \Psi_2 = \Phi \cdot w_2, \quad E_2 = -\frac{d\Psi_2}{dt}. \]

where \( B \) – the induction in the core (T); \( H(t) \) – the magnetic field strength (A/m); \( F_{\text{sum}} \) – the total magnetization (A); \( L \) – the average length of the magnetic lines (m); \( I_1 \) – the primary current (A); \( w_1 \) – the number of turns in the primary winding; \( I_2 \) – the secondary current (A); \( w_2 \) – the number of turns in the secondary winding; \( \Phi \) – the magnetic flux in the core (Wb); \( S \) – the area of the core (m²); \( \Psi_2 \) – the flux linkage of the secondary winding; \( E_2 \) – the EMF induced in the secondary winding (V).

In this model, the conversion of magnetic induction \( B \) from the strength \( H \) is performed by piecewise linear approximation of the main magnetization curve (MMC).

Calculated by (1) EMF of the secondary CT winding (at a given primary circuit current) is the control value in the model of the secondary CT circuit, consisting of the resistances of the secondary CT winding and the specified secondary load (figure 2b).

2. Simulation model of the CT based on the equations of dynamics of the Kadochnikov magnetic core remagnetization (2) [6, 7, 8]:

\[
\begin{align*}
\frac{dB}{dt} &= r \cdot (1 - \frac{B^2}{B_s^2}) \cdot [H(t) - H_{\text{sat}}(B)] \\
H(t) &= \frac{F_{\text{sum}}(t)}{L} \\
H_{\text{sat}} &= f(B) \\
F_{\text{sum}}(t) &= I_1(t) \cdot w_1 - I_2(t) \cdot w_2 \\
\Phi &= B(t) \cdot S \\
\Psi_2 &= \Phi(t) \cdot w_2 \\
E_2 &= -\frac{d\Psi_2}{dt}
\end{align*}
\]

where \( r \) – the losses on the eddy currents and magnetic viscosity; \( B_s \) – the magnetic induction at the core saturation; \( H_{\text{sat}}=f(B) \) – the static hysteresis loop.

In the TZLM model, based on equations (2), losses in the core steel for hysteresis and eddy currents were approximated by a constant active resistance connected in parallel to the magnetization branch. The resistance can be obtained in various ways, for example, calculated based on the geometry of the core, or experimental based on hysteresis loops.

The conversion of magnetic induction \( B \) from the strength \( H \) is performed by piecewise linear approximation of the specified magnetization characteristic (for example, the main magnetization curve of the MMC). This representation of the \( H_{\text{sat}} \) function (MMC and accounting for active losses in the core) gives a fairly accurate representation of the magnetization of the magnetic core steel [9].

3. Simulation model based on the Gills-Atherton equations (built-in model of the RSCAD software environment, Current Transformer block).

The non-linearity of the magnetization branch in the Current Transformer block is set either by the MMC (for known geometric parameters of the core) or by the Volt-Ampere characteristic (VAC).

The input values of simulation models are the primary current (if necessary, one can also model the electrical part of the primary circuit), and the output values are the EMF of the secondary circuit. The physical conditions for unambiguity are the number of turns of the primary and secondary circuits, the length of the average magnetic line, and the cross-sectional area.
Figure 2. Faraday’s model.

Figure 3. Model of Kadochnikov.

Figure 4. Gills-Atherton model (CT1 block, below-mathematical blocks for calculating H and B of the magnetic core of the secondary current of the CT and the secondary voltage with the model CT – B_mm and H_mm).
Thus, all three models contain a function describing the non-linearity of the magnetization branch (for example, the MMC), which can be taken from reference data or obtained experimentally. Due to the fact that the characteristics of CT samples of the same type made with cores made of electrical steel may differ significantly, CT models with experimentally obtained characteristics will have greater accuracy.

3. Determining parameters for CT models

To create models, the parameters of current transformers (steel magnetization curve, CT hysteresis loop parameters, secondary winding resistance, etc.) are required. These parameters were obtained using two methods.

3.1. Removing CT characteristics using Omicron CT Analyzer

CT Analyzer is a test system for protective and measuring CT that meets the IEEE and IEC standards. Using the indirect measurement method, the voltage signals are fed to the secondary winding, and the CT parameters are measured (figures 5-6). Based on the measurement results, the characteristics are calculated (for example, the volt-ampere characteristics VAC).

**Figure 5.** Test facility of a CT TZLM type.

**Figure 6.** Scheme of the experiment to obtain the VAC.

Based on the passport data obtained in the CT-Analyzer VAC report (according to IEC 60044-1) and calculated expressions (3 – 4), the main magnetization curve of the window of the transformer under study was constructed (figure 7)

\[
H = \frac{I_{CT_{EMS}} \cdot w_s}{L} \cdot 1.414; \\
B = \frac{U_{CT_{EMS}}}{4.44 \cdot 50 \cdot w_s \cdot S}
\]
Figure 7. Estimated MMC for CT TZLM type (obtained with CT Analyzer).

The standard test program with CT Analyzer allows you to get the basic parameters for building CT models, but it is not intended for obtaining partial hysteresis loops and calculating the resistance of the magnetization branch.

3.2. Obtaining TZLM characteristics using a real time simulation system RTDS  
The experiments were conducted as follows:

1. Assembling the circuit in accordance with figure 7 or figure 8 and supplying the primary current (from Omicron 356 CMC or PONOVO amplifiers) to the primary winding of the transformer under study: the number of turns of the primary winding N=20, the measuring noninductive shunt 0.1 Ohms, the resistance in the arms of the voltage divider 1.8 kOhm and 25.7 kOhm;

2. The primary current source control from Test Universe (for Omicron CMC 356) or RSCAD (for PONOVO PAC60Ci);

3. The removal of magnetization characteristics, primary current and secondary voltage waveforms (using RTDS GTAI analogue cards) when increasing the primary current from 6 A to 100 A;

4. Processing and comparing the experimental results obtained using Omicron CMC 356 and PONOVO PAC60Ci as the sources of the primary current with the MMC obtained using Omicron CT Analyzer.

Figure 8. Scheme for conducting experiments with Omicron CMC 356.
Figure 9. Scheme for conducting experiments with PONOVO PAC60Ci.

The appearance of the control program and output results is shown in figure 10.
The following experimental data were obtained:
- the time dependencies of the primary currents $I_1(t)$, secondary voltages $U_2(t)$;
- the time dependences of $B_{a_{it}}(t)$ induction and $H_{a_{prm}}(t)$ strength of the TZLM magnetic core;
- $B_{a_{it}}(H_{a_{prm}})$ private hysteresis loops.

The dependences are obtained when the core is magnetized in the XX mode and the primary current changes from 6 A to 100 A with a frequency of 50 Hz.

Additionally, the spectrum of the signals of the primary current and secondary voltage CT was calculated.

The results of the experiments with the primary current supply with Omicron CMC 356 and PONOVO-PAC60Ci generally coincided, however, when using Omicron CMC 356, the noise level in the primary current and secondary voltage signal was significantly lower, and it was possible to produce more primary current while maintaining its sinusoidality.

Based on the obtained $B_{a_{it}}(H_{a_{prm}})$ dependencies, the TZLM MMC is constructed (figure 11). The points on the MMC corresponded to the vertices (maxima of induction or magnetization) of the partial hysteresis loops. The vertices of the partial loops were different when constructing the maximum of induction or magnetization for loops that have the shape of an "ellipse" (for small values of primary currents, figure 10a).

Next, we compared the MMC obtained using CT Analyzer (orange curve in figure 12) and RTDS (blue curve in figure 12).

Comparison of MMC obtained on Omicron CT Analyzer complexes (recalculation of VAC in MMC) and RTDS (MMC obtained as the geometric location of the vertices of partial hysteresis loops when the core is magnetized) showed their discrepancy, which can be caused by the following:
- errors introduced by voltage dividers and current shunts when conducting RTDs circuits;
- errors introduced by the analog-to-digital Converter (ADC) RTDS;
- errors induced by the interference in the measuring circuit in the experiments with the RTDS;
- fewer points for building a MMC when conducting experiments with RTDS, and less accuracy of removing the "knee" of the MMC;
Figure 11. MMC TSLM (obtained with RTDS), the blue curve – the maximum for induction B, the purple one – the maximum for magnetization H.

Figure 12. Comparison of TZLM MMC obtained using CT Analyzer (orange curve) and RTDS (blue curve).

- the general method of constructing a MMC using partial hysteresis loops – in experiments with RTDS, the MMC was constructed in 2 ways, with a maximum of B and a maximum of H (not shown in the figures). The method of construction affects the type of characteristic on the linear section, but does not affect the estimate of the calculated saturation induction. Omicron CT Analyzer builds VAC based on integral values of currents and voltages.

Further, there are the models used the characteristics (VAC and MMC) obtained by Omicron CT Analyzer.

3.3. Determination of saturation induction by the received MMC

Based on the obtained experimental data (VAC and MMC), the saturation induction (inflection point) for TZLM was determined: 1.29 T (Omicron CT Analyzer data), 1.1 T (RTDS data).

4. Verification of CT models

For verification of CT models:

1. Using the scheme of the experiment (figures 8-9); the current is supplied using RTDS and amplifiers (Omicron CMC 356 and PONOVO PAC60Ci).

2. The output signals of the studied CT (physical signal) and simulation models of CT (according to claim 2) are compared.

All simulation models were tested at the same values of the primary values. An example of the experiment results is shown in figure 13, where the upper waveform is the primary current T.
Figure 13. Verification of CT TZLM type models.

In all three models of TT, the experimental characteristics obtained according to clause 3 were used. In the studied modes (no-load and secondary load CT 1 Ohm), the secondary currents of all models differ by no more than 10%. The models were accepted as reliable. They can be used, for example, to obtain the MMC and then calculate the saturation induction when conducting a physical experiment is not possible.

5. General algorithm for determining the time to saturation
The block diagram of the algorithm is shown in figure 14.
General method for calculating the time to saturation of CT:
1. Getting the original CT data from the manufacturer. If a CT sample is present, the experimental characteristics (magnetization curves or VAC, windings resistances) are taken using Omicron CT Analyzer and RTDS.
2. Getting initial data on the CT operating mode short-circuit currents (maximum values of the short-circuit current amplitude and the constant attenuation of the aperiodic component), the secondary load of the CT.
3. Input of the received initial data into the CT simulation models (section 2 of the article).
4. Calculating CT models based on the received initial data and characteristics. Conducting computational experiments to obtain the CT MMC or VAC, CT secondary currents at specified modes and secondary loads.
5. Based on the calculation of the model CT, determining the time to saturation of the CT, in order to ensure the correct operation of the RPA.

6. Conclusion
Simulation models of CT in the RSCAD environment were developed and verified, which allow simulating both steady-state and transient modes with sufficient accuracy, taking into account the influence of saturation and residual magnetization of the magnetic core. Based on the research, an algorithm for determining the time to saturation was developed. The models can be used to determine the saturation time taking into account the real characteristics of electromagnetic current transformers, the axial magnetization, the multiplicity of the short-circuit current, etc. Using these models, it is also possible to check the stability of various RPA algorithms during saturation and residual magnetization of the CT.

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