Current sensor designed for usage with digital control systems of electric grid

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Abstract **–** The magnetic characteristics of nano-crystalline alloy MN-11 tape-wound magnetic core are studied and a mathematical model of the current transformer with such magnetic core is made in the form of block diagram of the servo system. Designed and manufactured current sensor for digital control systems in the form of high-precision current transformer with a specified minimum value of the rated instrument security factor of the secondary winding. Experimentally confirmed the high level of metrological performances of the sensor and their practical stability in the frequency range 50-2000 Hz.

Keywords*:* nano-crystalline alloy, the sensor, the mathematical model, the error.

I. Introduction

One of the main trends of modern measuring transducers (MT) of electric quantities in the electric power industry is the increasing use of microelectronics. The most promising is the use of various intellectual MT, which form the primary measurement signal and then make its normalization, transformation, and previous processing using the integrated microprocessor with the appropriate functionality. If the MT has interface for communication with external devices for processing measured signal, it can be classified as a system MT. And in this case, it is the simplest data acquisition and processing system. Using such current MT (MCT) makes it possible to greatly simplify the structure of information-measuring systems which are components of automated control systems of electric power objects, and also to improve their metrological performances (MP), efficiency and reliability.

To date, implementation of such transformers is regulated by international standard [1]. The latter allows the use of the sensors which are based on the different physical effects (transformer, optical, etc.) for development of such MCT. In recent times, an optical engineering makes progress in developing of MCT sensors for high-tension electricity network (EN). The optical technology makes it possible to get rid of such disadvantages of electromagnetic current sensors as magnetic saturation, flammable paper-oil insulation and others. However, it is clear that the use of fiber-optical current transformers (FOCT) is functionally and economically sound primarily in the high voltage EN, because of disadvantages of electromagnetic current transformers (CT) are the most important in such EN. In world practice, FOCT used in EN with voltage level from 765 to 69 kV. But the use of such CTs in electric grid is economically inexpediency.

However, progress in research and production of amorphous and nano-crystalline magnetic materials and their use as CT magnetic core made it technical possible to building a digital MCT, especially for the electric grid, with electromagnetic sensors with unique MP and with low weight and dimensions.

II. Impact of new magnetic materials properties on the characteristics of current transformers

The main advantages of new magnetic materials are high permeability, low magnetic core loss, low value of residual induction and relatively high value of the saturation induction. The high magnetic permeability of these cores allows to design CT, accuracy class 0,2S and above with a single-turn primary winding, even for relatively small values of the rated primary current. Single-turn primary winding simplifies the CT design, reducing materials consumption of the transformer and its dimensions. This reduces the parasitic reactance parameters of CT, which by-turn improves the frequency and dynamic properties of the transformer. The low magnetic losses also make it possible to increase frequency range of CT.

The low value of residual induction in the cores of amorphous and nano-crystalline alloys provides a CT operation without a significant increase of errors after core magnetization of aperiodic component of current in the transient state. CT with electrical steel cores, after such stress, may operate dozens of hours with high error, which is significantly exceeding the permissible limits. The accuracy of the new magnetic materials CT is resumed immediately after termination of the transient state, providing high accuracy and reliability of electricity metering in the postemergency state.

The application of new magnetic materials for sensors of digital current transducer also provides the optimal solution of contradictory problem: simultaneously providing a fixed security factor of instruments that are connected into CT secondary circuit and the high accuracy class of its measurement winding. The range of technical saturation induction of amorphous and nano-crystalline alloys cores is at a level 1.1-1.2 T, but an inflection point of the magnetization characteristic is at a level 0.9-0.95 T. This allows us to create CT with low values of the rated instrument security factor, up to a magnitude of 1.5-2.5. In this case, secondary current of the CT is limited to a safe level due to core saturation. But due to the low magnetizing force, it is remain high CT accuracy to such an extent when the primary current is becoming an equal to the security current.

III. The mathematical model of the current sensor

Mathematical modeling of CT with new amorphous or nano-crystalline magnetic materials core carried out taking into account the peculiarities of the magnetic characteristics of such materials. The magnetic loss angle is one of the important magnetic characteristics used in the calculation of current error and phase displacement of the CT. In amorphous and nano-crystalline magnetic materials, calculation of the magnetic loss angle is difficult because of the small magnitude power of the magnetic losses, which are usually used for calculating of loss angle [2]. Determination of the loss angle at low frequencies, and on samples with small volume is very difficult. In this case it is advisable to determine the loss angle under the circuit design Figure 1 as the angle between the magnetizing current (magnetizing force) in the magnetizing winding w_{1m} and the induction winding voltage w_{2i} (magnetic flux) in the light of the fact that the voltage and magnetic flux are shifted by an angle of 90 degrees.

The generator G signal through a power amplifier PA and the power transformer PT is supplied to magnetizing winding w_{1m} of test specimen T. Phase meter PhM steady operation at the distorted form of intensity and induction of a magnetic field in the core is provided with voltage shapers ShV1 and ShV2 of the right-angled form. Voltage from the induction winding w_{2i} and from shunt R_{sh} is supplied to their terminals. Output voltages are in phase to the fundamental harmonics of voltage, which in turn are proportional to the intensity and induction of a magnetic field in the studied magnetic core.

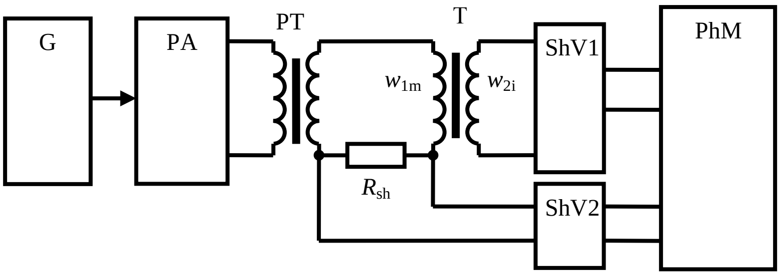


Figure 1. Loss angle determination

This way had been investigated dependence of magnetic loss angle on induction at 50 Hz in the new amorphous and nano-crystalline materials cores of small mass and with low magnetic losses (Figure 2).

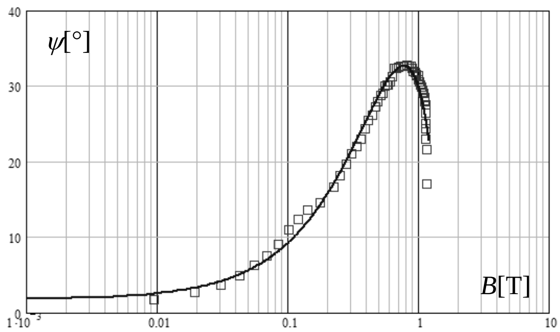


Figure 2. Dependence of magnetic loss angle ψ on induction B at 50 Hz for a magnetic core of MN-11 alloy

These dependences used to calculate the current error and phase displacement of the CT of new magnetic materials, as well as to determine the power and resistance of losses. The latter uses for constructing transformers mathematical models in the form of block diagrams of servo systems. This allowed to calculate more accurately the parameters of mathematical models and the errors of CT.

Block diagram of electromagnetic CT as a servo system (automatic control system) (Figure 3) can be constructed based on the following reasoning. The input value of such a servo system is the primary current I_1, and the output value - the secondary current I_2, which is exactly equal to the input value in the scale w_1/w_2.

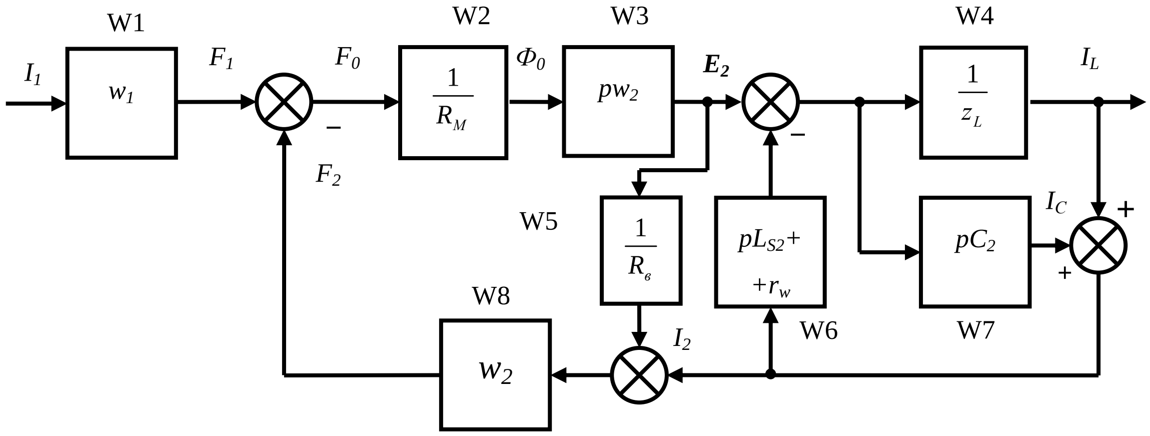


Figure 3. Block diagram of the current sensor

The primary current I_1 of CT, flowing through the primary winding w_1, creates the primary magnetomotive force (mmf) $F_1=I_1 \cdot w_1$ (link W1 with the transmission coefficient w_1). The secondary current I_2 of CT, which flows through the secondary winding w_2, creates a secondary mmf $F_2=I_2 \cdot w_2$ (link W8 with the transmission coefficient w_2).

The primary F_1 and secondary F_2 mmf are directed towards each other in a transformer magnetic core. Resulting mmf $F_0=I_0 \cdot w_1$ is equal to the difference between F_1 and F_2, where I_0 - magnetizing current (it is the first adder on the diagram).·Under the influence of magnetizing force F_0 in the CT core produces a magnetic flux $\Phi_0 = \frac{F_0}{R_M}$, where $R_M = \frac{l}{\mu \cdot S}$, and l, S, μ are the mean length of magnetic line, cross-sectional area and the absolute permeability of the CT core (link W2). Under the action of magnetizing flux Φ_0 in the secondary winding w_2 produces an electromotive force $E_2 = -\frac{d}{dt} \cdot w_2 \cdot \Phi_0 = -p \cdot w_2 \cdot \Phi_0$ (link W3), where p - Laplacian. The voltage E_2 is inducting secondary current I_2 in the secondary CT winding w_2. I_2 consists of the sum of the currents: the current $I_L = E_2 \cdot \frac{1}{Z_L}$ at the load Z_L and the current $I_C=E_2 pC_2$ at a self-capacitance of the secondary winding w_2. Respectively, on the block diagram they are the link W4 with a coefficient of transmission $1/Z_L$, and the W7 link with a coefficient of transmission pC_2 and the adder. At a total resistance of the secondary winding $Z_{w2}= r_2 +pL_{S2}$, where r_2 is internal resistance of the secondary winding, and L_{S2} is its leakage inductance, the current I_2 creates voltage drop, which reduces voltage applied to Z_L and C_2. On the block diagram it is shown as the link W6 and adder, which create a local negative feedback, and reduce the voltage E_2. Effect of loss resistance R_B, at which the current I_B increases the CT error, is taken into account in the link W5 with adder.

Thus, in developing block diagram of electromagnetic CT, as servo system, it takes into account the parasitic parameters of the secondary winding and core losses resistance. Using Mason's rule concerning the block diagram Figure 3, we obtain the transfer function of the CT:

$$W_{CT}(p) = \frac{I_L}{I_1} = \frac{w_1}{w_2} \cdot \frac{b_0 p}{a_0 p^3 + a_1 p^2 + a_2 p + a_3},$$

where a_0, a_1, a_2, a_3, b_0 are the factors which depend on the parameters of the sensor.

In the case of the frequency range in which we can neglect the capacity of the transformer secondary winding, and if the load resistance is equal $Z_L = pL_L + R_L$, the transfer function simplifies to:

$$W_{CT}(p) = \frac{w_1}{w_2} \cdot \frac{pT_2}{p^2 T_B T_\Sigma + p\left[T_2(1+k) + T_\Sigma\right] + 1},$$

where $T_2 = \dfrac{L_0}{R_H + r_2}$; $T_\Sigma = \dfrac{L_H + L_{S2}}{R_H + r_2}$; $T_B = \dfrac{L_0}{R_B}$; $k = \dfrac{R_H + r_2}{R_B}$; $L_0 = \dfrac{\mu \cdot S}{l} \cdot w_2^2$.

Thus, we define the transfer function of the CT, which takes into account the resistance losses in the transformer magnetic core. This function consists of both linear T_Σ and nonlinear T_B time constants, the nonlinearity is determined by the nonlinearity of magnetization inductance L_0 of the transformer core and a nonlinear resistance losses R_B.

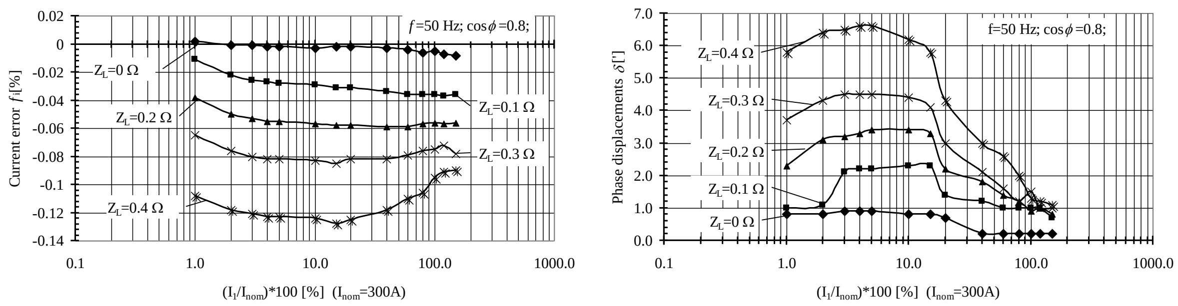
Resistance losses R_B may calculate on the known angle of the losses as follows:

$$R_B = \frac{2\pi f}{tg\psi} \cdot \mu_0 \mu_a \cdot \frac{\eta S}{l} \cdot w_2^2$$

where f is primary current frequency; μ_0 is permeability of free space; μ_a is relative permeability; η is material filling factor of core section.

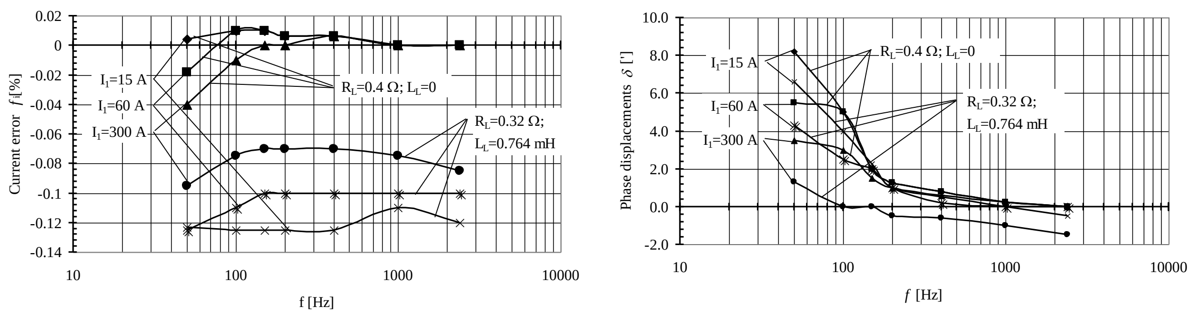
IV. Experimental researches

On the basis of the researches the procedure of calculation of design parameters of the electromagnetic system of CT is developed. Procedure of calculation allows to design measuring transformers with the specified rated instrument security factor and high accuracy class. This procedure was used to calculate experimental models of CTs at nominal currents 300 and 1000 A with the rated instrument security factor equal to 2.5 and 1.5 accordingly. These CTs were made and tested. The experimental results confirmed high metrological performances of this CTs and adequacy of the used mathematical models and calculation procedure (figure 4 - 5).



a) b)

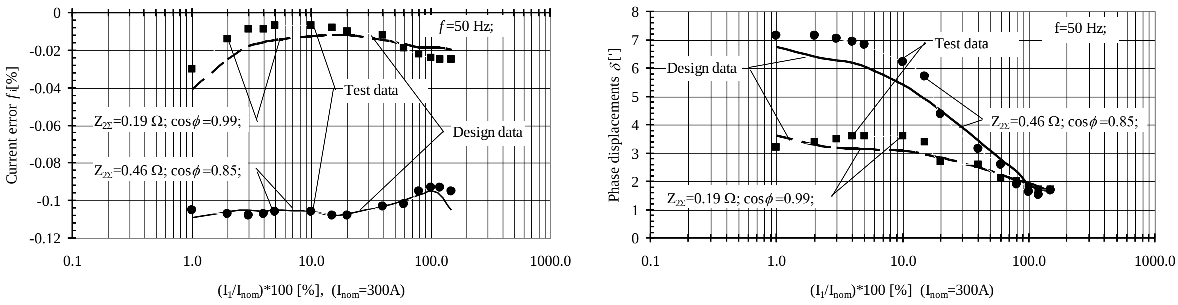
Figure 4. Dependences of current error (a) and phase displacement (b) of CT 300/5 A on the value of primary current at $\cos\varphi$=0.8 at the different values of burden (S_{2nom}= 10 VA)



a) b)

Figure 5. Dependences of current error (a) and phase displacement (b) of CT 300/5 A on frequency at the different values of primary current and burden

The absolute error of calculation of a current error is less than 0,02 % at a known impedance of a secondary circuit of the current transformer and known magnetic characteristics of its core. The absolute error of calculation of a phase displacement does not exceed 1 minute (figure 6).



a) b)

Figure 6. Design and test dependences of current error (a) and phase displacement (b) of CT 300/5 A on the value of primary current at frequency 50 Hz at the different values of impedances of secondary circuit of transformer

V. Conclusions

Application of amorphous and nano-crystalline magnetic materials in the current sensors production for usage with the digital control systems by distribution networks allows substantially to decrease their errors, weights and dimensions, to extend the frequency range of current measurement, to promote stability of metrological performances in a wide frequency range.

Proposed mathematical model and calculation procedure of design parameters of the CT electromagnetic system make scientific and technical basis for the design of the high accuracy and reliable measuring current transformers, which support the international standards.

References

[1] International Standard IEC 60044: Instrument transformers.
[2] Kifer I.I., *Tests of ferromagnetic materials*, «Energy», Moscow, 1969, 360 p.