Study of the influence of magnetic properties of amorphic alloys on the electromagnetic field of current transformers with a short-closed circuit

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Abstract. The optimal functioning of the electric power industry can be ensured only if the important problem is successfully resolved by reliable measurement of electrical quantities, such as voltage, current, and power. In industry, a current transformer is often used as a current meter, which makes it possible to obtain an AC current measurement result with high accuracy. Structurally, the current transformer has a significant drawback, which is that the opening of the secondary measuring winding leads to an emergency. To solve this problem, you can apply the improved design of the current transformer squirrel-cage current transformer (in the form of a cylinder or ring). This article presents the results of two-dimensional modeling of the electromagnetic field of current transformers with a short-circuited coil, with cores made of different grades of amorphous iron in the ELCUT software package. In addition, the results of experimental studies of the improved design of the current transformer are presented. An analysis of the results allows us to conclude that the use of a core made of amorphous iron with a higher magnetic permeability will lead to economic benefits and make the measurement process more energy efficient.

In [1-2], the author proved the advantages of using the improved design of the current transformer. These advantages are explained by the design features of the current transformer, consisting in the presence of an electrically conductive coil in the form of a cylinder and a measuring winding operating in idle mode and made of a small cross-section wire. In an industrial current transformer, the secondary winding is short-circuited and must have a sufficiently large cross section. At the same time, the main disadvantage of the current transformer used in industry is the danger of opening the measuring signal winding during the flow of the measured current, since there are dangerous overvoltages, which in some cases lead to emergency situations. The proposed design [1-2] a squirrel-cage current transformer does not have this drawback, while the time waveform coincides with the time waveform of the measured current and there is no phase shift between them. These studies were conducted for samples in which the core was made of electrical steel.

Currently, transformers, in particular current transformers whose cores are made of amorphous iron-based alloys, have become increasingly popular in the electric power industry, which is explained by the excellent properties of these alloys [3-4].

The use of these alloys as electrotechnical materials from which the cores of current transformers are made makes it possible to improve their electromagnetic characteristics. If we compare amorphous alloys with other electrical materials, such as electrical steel, permalloy and ferrites, we can note the...
differences, which are significantly lower values of specific magnetic losses, high initial and maximum relative magnetic permeability and saturation induction, especially at high frequencies.

Amorphous alloy is a special class of precision alloys, which is distinguished by its structure, complex physical properties and manufacturing method [5]. The presence of elements such as boron, carbon, phosphorus and others in the composition of amorphous alloys makes it possible to preserve the amorphous structure. Such a composition makes it possible to reduce the maximum values of saturation induction in amorphous alloys by about 20% compared with pure iron and increase the temperature coefficient of magnetic properties [6]. In addition, the presence of these elements can increase the electrical resistance, increase the hardness and strength of amorphous alloys, as well as their corrosion resistance [7].

The characteristics of products from amorphous alloys depend on their chemical structure, casting quality and processing conditions, such as winding, applying an interlayer insulation coating and thermomagnetic processing [8]. Amorphous alloys are widely used in modern electrical devices and radio equipment due to a set of unique properties [9]. It has been proved that the use of amorphous alloys as the material of the core of transformers, including current, allows not only to save electricity, but also brings environmental benefits [10-12].

An analysis of all the advantages of amorphous alloys allows us to conclude that their use as a material of the core of a squirrel-cage current transformer will improve the electromagnetic characteristics.

To confirm this, this article presents the results of studies using the finite element method of two samples of squirrel cage current transformers in the ELCUT software package. For objectivity in assessing the results of engineering analysis and two-dimensional modeling, the studied models of two samples will have the same design parameters (geometric dimensions and material of the bus with current, short-circuited turn, etc.). The difference will only be in the different magnetic characteristics of the cores. The results of the study of samples of current transformers with short-circuited turns (rings or cylinders), the cores of which are made of electrical steel and amorphous iron with a relative magnetic permeability of 10,000, are presented in [13-14]. The relative magnetic permeability of electrical steel, and other electrical materials used for the manufacture of transformer cores, can be obtained by testing materials in their entire range of characteristics [15].

Table 1 presents the values of saturation induction and relative magnetic permeability for two samples.

| MAGNETIC PROPERTIES       | Sample No. 1 | Sample No. 2 |
|----------------------------|--------------|--------------|
| Relative magnetic permeability | 10000        | 35000        |
| Magnetic induction of saturation | More than 1,1 |              |

Due to the fact that the short-circuited coil (cylinder) has a shielding effect, the working magnetic induction of the core will be many times less than the saturation induction for all the samples under study. Due to the insignificant values of the scattering fluxes, scattering through end surfaces can be ignored. In this regard, the study of samples can be considered as a linear two-dimensional problem. Based on this, it can be concluded that the ELCUT software package [16] for modeling the electromagnetic field of the samples under study and engineering calculations of electromagnetic parameters is the most acceptable option.

For the study, we assume that the core materials of the samples under study are linear, eddy currents in the cores are very small, and there are no hysteresis losses.

The geometric dimensions for the study are shown in figure 1 (dimensions are presented in millimeters). The primary winding is represented by one winding (a bus with a measured current, the effective value of which is 45 A) made of copper, a short-circuited winding is made of aluminum.
Amorphous iron cores are annealed using a magnetic field, this allows you to achieve the minimum possible loss in the core, but the annealing process makes the material brittle, so the core is placed in a protective plastic container (box) [17-18]. Figure 2 shows the geometric dimensions of the protective box (in millimeters). Consideration of the dimensions of the protective box is necessary for the correct construction of the model in the ELCUT software package, since for the studied models with cores made of amorphous iron, it must be taken into account that the short-circuited coil will be located directly on the protective box.

![Figure 1](image1.png)  
**Figure 1.** The geometric dimensions of the core (mm).  

![Figure 2](image2.png)  
**Figure 2.** The geometric dimensions of the protective split box (mm).

Figure 3 shows a cross section of a squirrel-cage current transformer. The short-circuited coil is made of aluminum, its thickness is 2 mm, length 10 mm.

![Figure 3](image3.png)  
**Figure 3.** Cross section of a squirrel-cage current transformer (size in millimeters): 1 - a protective plastic container; 2 - amorphous iron core; 3 - bus with measured current; 4 - shorted turn.

The results of two-dimensional modeling of the electromagnetic field of two samples with different brands of amorphous iron, of which the cores are made, are shown in the figures: figure 4 - sample 1 (amorphous iron (μ_{отн}=10000)), figure 5 - sample 2 (amorphous iron (μ_{отн}=35000)).
Figure 4. The pattern of the distribution of the lines of force of the magnetic field induction of the investigated sample 1 ($\mu_{\text{отн}}=10000$).

Figure 5. The pattern of the distribution of the lines of force of the magnetic field induction of the investigated sample 2 ($\mu_{\text{rel}} = 35000$).

The results of the engineering calculation of the complex magnetic flux value in the core section 1-1 in the ELCUT software package are shown in table 2.

| Test samples   | $\Phi_m, 10^{-6}$ Vb | $\varphi, ^\circ$ |
|---------------|----------------------|-------------------|
| Sample 1      | 8.1464               | 90.634            |
| Sample 2      | 8.1415               | 90.104            |

After analyzing the results of the study of samples of current transformers with a short-circuited turn (ring), we can conclude that the use of an amorphous iron-based alloy with a relative magnetic permeability of 35,000 as a core material is more expedient and economically preferable, since the value of the phase measurement error decreases.

The signal winding in the samples under study is located under a short-circuited turn. To increase the value of the voltage signal received from the signal winding, it is necessary to increase the value of the magnetic flux in the cross section of the core under the signal winding. For this purpose, we studied the electromagnetic field of a sample of a current transformer with a short-circuited coil, in which the length of the short-circuited coil was reduced from 10 mm to 6 mm.

An analysis of the results of engineering calculation of the magnetic flux value (table 3) and a comparison with the calculation results shown in table 2 allow us to conclude that the use of a shorter closed loop length (6 mm) is more appropriate for energy and economic indicators. This is because reducing the length of the coil will increase the value of the magnetic flux (increase the signal) and reduce the phase error to zero, in addition, you can reduce the cost of producing a short-circuited coil and a current transformer with a short-circuited coil as a whole.
Figure 6. The pattern of the distribution of the magnetic field lines of the magnetic field of the investigated sample 2 ($\mu_{rel} = 35000$) with a coil length of 6 mm.

Table 3. The value of the magnetic flux in section 1-1 with a short-circuit length of 6 mm.

| Test sample | $\Phi_m, 10^{-5}$ Vb | $\varphi, ^\circ$ |
|-------------|---------------------|------------------|
| Sample 2    | 1.3641              | 90.01            |

1. The use of a short-circuited current transformer with a core made of amorphous iron makes it possible to obtain a sufficient signal level in a convenient form for registration by measuring microprocessor complexes.

2. The use of a current transformer with a short-circuited coil of amorphous iron grades with a higher value of relative magnetic permeability as the core material will allow:

- reduce the phase error of current measurement;
- reduce costs in the production of short-circuited turns;
- obtain a higher signal level from the measuring winding of the transformer with the short-circuited turn.

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