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# 3D FIELD-CIRCUIT ANALYSIS OF MEASUREMENT PROPERTIES OF CURRENT TRANSFORMERS WITH AXIALLY AND RADIALLY CONNECTED CORES MADE OF DIFFERENT MAGNETIC MATERIALS

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**Abstract**—We report results continuing the research which looks at the influence of two different magnetic materials in a core construction on the transformation errors of a current transformer [1]. In this paper we consider the behaviour of two different magnetic materials in a core. They are joined in a different way to the previous study; not axially (one-by-one), but also radially (one inside the second). We have conducted 3D analyses of the electromagnetic field distribution for different cases of current transformers and carried out computations based on the finite-element numerical method. We compare the results with tests of real-life models.

## 1. INTRODUCTION

This work continues the research which looks at the influence of two different magnetic materials in a core construction on the transformation errors of a measuring current transformer [1]. A measuring current transformer is an element of a measuring system, which as a device that transforms signals, adds its transformation errors to measuring values. IEC standard obliges designers to determine and limit these errors. The current error and the phase displacement of current transformers indicate the accuracy class of a designed current transformer [11]. The improvement of current transformers measurement properties, without changing the dimensions, requires magnetic materials of an improved quality.

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Nanocrystalline materials have better magnetic properties than cold rolled electrical steels. However, these materials cannot be separately used in current transformers because of the low value of their saturation magnetic flux density [12]. Therefore, in practice, to improve transformers parameters, constructors combine two different ferromagnetic materials; transformer steel and nanocrystalline materials [2, 3, 6, 8].

In the previous paper we presented the constructional solutions which include new magnetic materials (toroidal nanocrystalline cores made from material type Fe-Si-Cu-Nb-Si-B). The results of the analysing the measurement properties of cores connected axially (one-by-one) with different proportions of magnetic materials used were shown.

The used field-circuit method has given the possibility to accurately determine the current error and the phase displacement of current transformers as well as equivalent magnetic characteristics of cores made of different materials.

In this paper we consider the behaviour of core magnetic materials connected in different ways; axially (one-by-one) and radially (one inside the second).

## 2. A MATHEMATICAL MODEL

Analysis has been carried out using the 3D field-and-circuit method [1, 4, 9]. The mathematical model was described in detail in the paper [1].

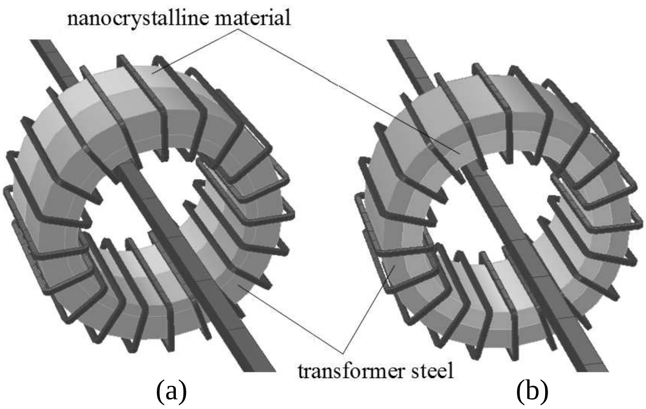



**Figure 1.** The 3D models of the measuring current transformers 100 A/5 A, (a) materials joined axially (one-by-one), and (b) radially (one inside the second) 1-transformer steel 2-nanocrystalline material.

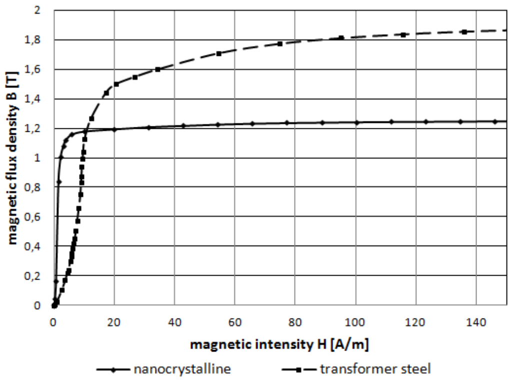



**Figure 2.** Magnetic characteristics of used core materials (test).

The non-linear magnetic characteristic BH of the ferromagnetic materials was taken into account. Like the previous paper [1] the method which takes into account power losses in laminated cores [5, 10] was applied. It is based on introducing a hypothetical homogeneous core of conductivity $\sigma$ equivalent to the real core of the same dimensions, was applied in the research described in this work.

As examples, the measuring current transformers 100 A/5 A were considered. The primary winding of current transformers was a bus bar and the secondary winding was wound on a magnetic toroidal core made from combined steel and nanocrystalline material (Figure 1).

All versions of cores have the same dimensions (external and internal diameters of the core are, respectively, 61 and 42 mm; height is 30 mm) and total cross section ST $= 2.85\,\mathrm{cm}^2$, with 20 turns on the secondary winding. The cores were wound of cold rolled electrical steel tape and nanocrystalline tape (Figure 2).

Nanocrystalline tape is made from material type Fe-Si-Cu-Nb-Si-B [12] and applied in current transformer cores. The permeability values of nanocrystalline are significantly higher than of electrical steel. The advantages of nanocrystalline cores are their better stability at temperatures of up to 200°C and minimal power losses. A disadvantage is the lower saturation of magnetic flux density Bs $\approx 1.2$ T. The current transformers with nanokrystaline core very quickly saturate and then the values of current errors and phase displacements increase rapidly.

3D field analyses and tests were performed for different types of current transformer toroidal cores [7]. The five versions of different material proportions were taken into account:

- A — transformer steel,
- B — 2/3 transformer steel and 1/3 nanocrystalline,
- C — 1/2 transformer steel and 1/2 nanocrystalline,
- D — 1/3 transformer steel and 2/3 nanocrystalline,
- E — nanocrystalline.

and for versions B, C, D two kinds: for core magnetic materials joined axially (one-by-one) (Figure 1(a)) and radially (one inside the second) (Figure 1(b)). The cross sections of two core parts joined axially and radially are the same ($S_{\mathrm{FeA}} = S_{\mathrm{FeR}}$ and $S_{\mathrm{ncA}} = S_{\mathrm{ncR}}$) and in accordance with the material proportions.

## 3. COMPUTED RESULTS AND EXPERIMENTS

The current error and the phase displacement have been computed according to standard [11] based on forced primary current and a computed secondary current. The current error and phase displacement of the current transformer computed at a steady state were performed for the load $S_n = 2.5\,\mathrm{VA}$, $\cos\varphi = 0.8$ and required RMS values of the sinusoidal primary current. Rated primary current $I_{pn}$ is equal to 100 A. Consequently, this would require making and testing at least eight prototypes with differently constructed cores.

The field-and-circuit computations were performed using the professional software 3D for the systems shown in Figure 1 using a dividing mesh of 9954711 nodes. Analysis of accuracy was performed by changing of the mesh size. The mesh for 3D model was result of accuracy analysis. Further mesh refinement did not change the solution.

The measurements were performed in the same conditions using the measuring bridge of K535 type with an automatic comparator manufactured by the company ROCTOK PRIBOR Ltd. [13]. In our case was tested current transformer 100 A/5 A and the accuracy was below ±0.7% for $\Delta(\Delta i)/\Delta i$ current error and ±1.3% for phase displacement $\Delta(\delta i)/\delta i$.

In order to check the conformity of the both methods, the results of tests and 3D analysis carried out in the same condition for current transformer with a core made of steel (A) or nanocrystalline material (E-field distributions shown in Figure 3) were compared. Figure 4 shows a comparison of the current error and the phase displacement characteristics of the discussed current transformers. The curves of error characteristics obtained by tests and computations using the field-circuit method are close to each other.

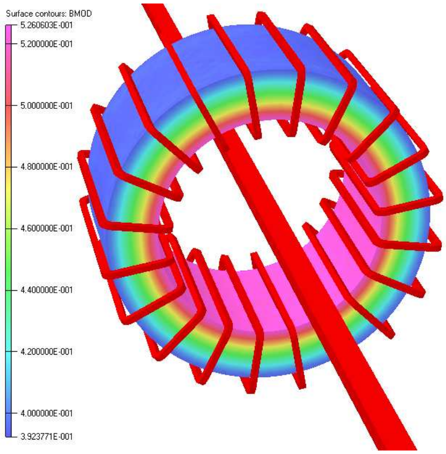
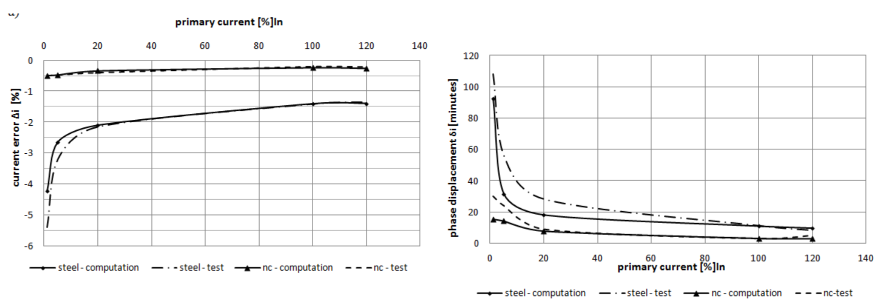



**Figure 3.** Magnetic flux density distributions [T] of measuring current transformers with core made from nanocrystalline material at the rated primary current $I_{pn} = 100\,\text{A}$ and burden $S_n = 2.5\,\text{VA}$ ($\cos\varphi = 0.8$).




(a) (b)

**Figure 4.** Results from computations and tests for the current transformers with the core made from transformer steel and nanocrystalline material at the same load $S_n = 2.5\,\text{VA}$, $\cos\varphi = 0.8$ ($I_{pn} = 100\,\text{A}$), (a) current error, and (b) phase displacement characteristics of the current transformer.

The next challenge was recognizing the influence of the different proportions of two combined materials and a way of connecting the measuring properties of the current transformer.

In Figure 5 we observe that magnetic flux passes mainly through the nanocrystalline part of the core.

Figures 6 and 7 show that there are no significant differences in measuring properties of current transformers with the core connected

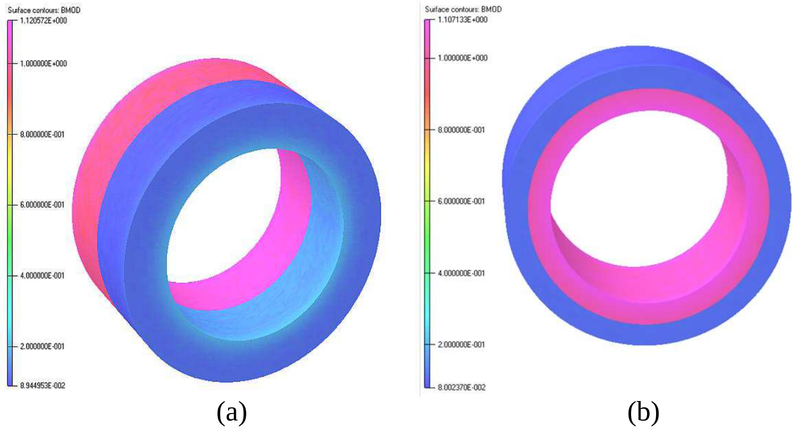



**Figure 5.** Magnetic flux density distributions [T] of measuring current transformers version C with the core made from combined steel and nanocrystalline material at the same primary current, (a) materials joined axially, and (b) radially.

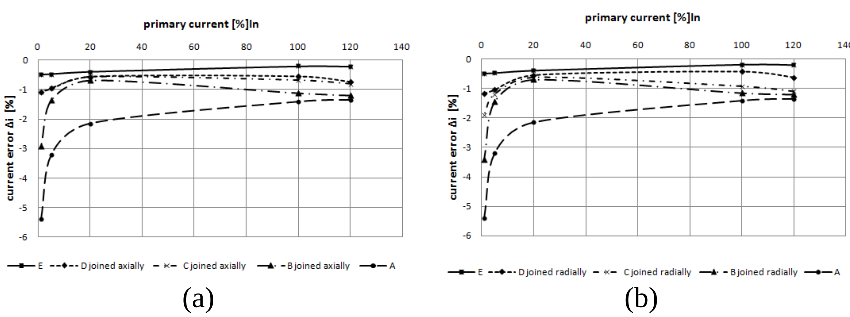



**Figure 6.** Results from tests of current error for the current transformers with combined core using different proportions of steel and nanocrystalline material, at the same load $S_n = 2.5\,\mathrm{VA}$, $\cos\varphi = 0.8$ ($I_{pn} = 100\,\mathrm{A}$), (a) materials joined axially, and (b) radially.

axially and radially. But proportions of steel and nanocrystalline material in combined cores have of course a great influence on their measuring properties, especially current error.

Constructors designing current transformers usually use simple analytical computations based on the equivalent circuit of a current transformer and the equivalent magnetic characteristics of the core. Therefore they need the equivalent magnetic characteristics

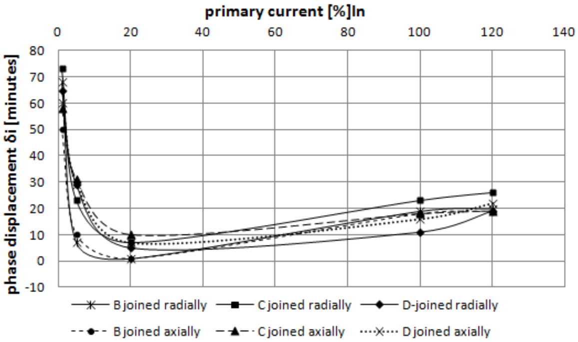



**Figure 7.** Comparison current error and phase displacement characteristics for the current transformers with a core combined axially and radially and different joint proportions (B, C, D), at the same load $S_n = 2.5\,\mathrm{VA}$, $\cos\varphi = 0.8$ ($I_{pn} = 100\,\mathrm{A}$)).

of two different connected magnetic materials. Without the field computations it is impossible to predict the magnetic field distribution and in consequence the equivalent magnetic characteristics for joined cores. Therefore the determination of an equivalent magnetic characteristic from the combination of two different magnetic materials by analytical computation causes serious problems.

Like the previous paper an equivalent magnetic characteristic from the combination of two different magnetic materials was determined point-by-point using the field-circuit method [4].

The computations were performed using a method analogous to the one used in the research carried out to determine the magnetic characteristic of the real-life model of the core. In this method the values of the primary current are forced and the values of induced secondary voltage are measured.

For example the field distributions in the cores version C in two types of connections of magnetic materials are shown below. In Figures 8 and 9 one can observe that magnetic flux pass mainly through the nanocrystalline part of the core. If the saturation level increases the ratio of flux going through nanocrystalline and steel core parts decreases.

If the primary current increases so that first nanocrystalline material is saturated because it's magnetic permeability is bigger and reluctance is smaller than transformer steel. The magnetic flux density in this part of the core achieves constant value about 1.2 T at saturated state. Then the magnetic flux gets in transformer steel and the level of magnetic flux density in steel rises.

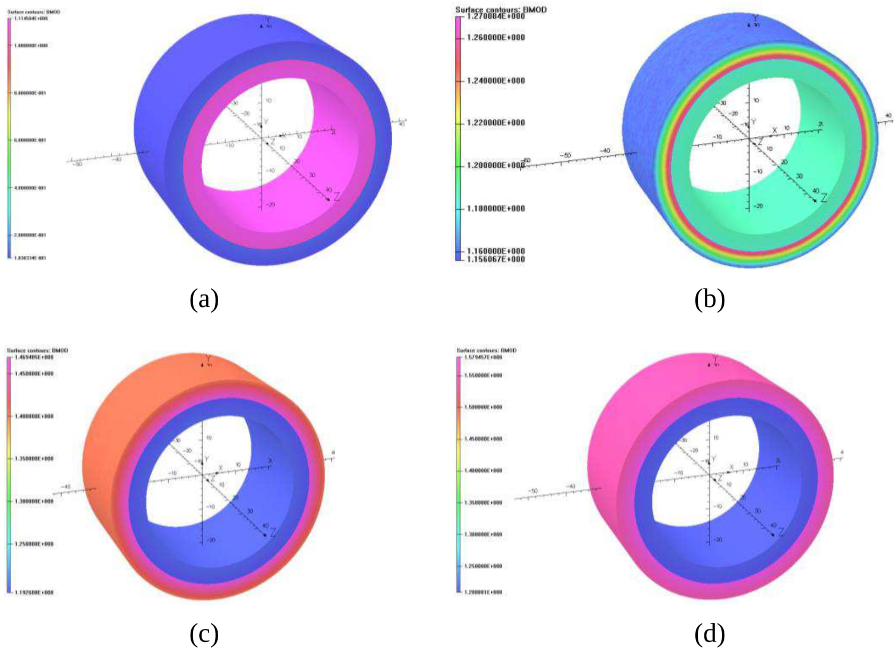



**Figure 8.** Magnetic flux density distributions [T] of measuring current transformers version C with core joined radially two materials (steel and nanocrystalline) at the primary current equal, (a) 0.5 A, (b) 2 A, (c) 30 A, (d) 200 A.

Figure 10 shows that equivalent magnetic characteristics are the same independently of whether the core materials are joined axially or radially. But the difference in the shape of the curves depends only on proportions of steel and nanocrystalline material in the combined core. The equivalent characteristics of the cores with higher contents of nanocrystalline material are saturated at a smaller value of magnetic flux density than others but at low value of magnetic field intensity its magnetic permeability are bigger and the properties of the core are better.

The analysis of relationship between measuring properties of current transformers and nanocrystalline contents in a combined core was carried out.

Comparison measuring errors from test and field computations for current transformers, with cores connected in different proportions and in different ways, at the rated condition are presented in Figure 11.

The values of current errors and phase displacements (Figure 11) are the result of considered computations and tests. The results

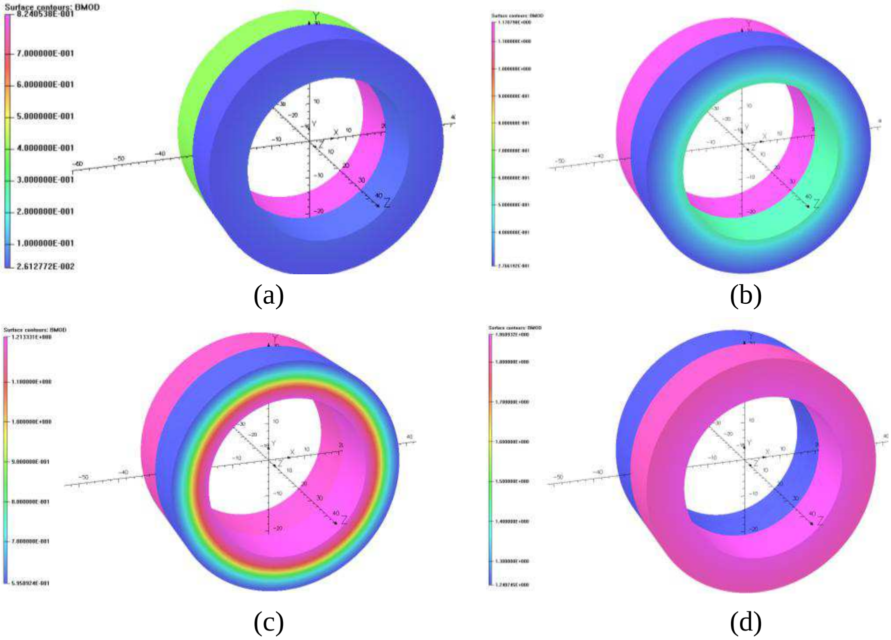



**Figure 9.** Magnetic flux density distributions [T] of measuring current transformers version C with core joined axially two materials (steel and nanocrystalline) at the primary current equal, (a) 0.2 A, (b) 1 A, (c) 1.5 A, (d) 200 A.

obtained for the same current transformer using 3D analysis and tests were compared. Although the phase displacement characteristic of the current transformer with a core made of steel fulfils the class accuracy a 0.5 S requirement, the current error characteristic goes outside of the class limits.

If the content of nanocrystalline in combination increases the current error decreases. The magnetic permeability values of nanocrystalline magnetic materials are significantly higher and than permeability of electrical steel. In consequences the values of current errors and phase displacements are smaller in current transformer with nanocrystalline core. However, also core losses have some influence on measurement properties of current transformers. It is commonly known that if the core losses decrease the current error decreases and the phase displacement rises.

Although the equivalent magnetic characteristic of material for the same proportions of nanocrystalline for both ways of a joined core is the same the current error is little different. The difference is caused by different core losses. Although the cross sections of two core parts in a case joined axially and radially are the same ($S_{\mathrm{FeA}} = S_{\mathrm{FeR}}$ and $S_{\mathrm{ncA}} = S_{\mathrm{ncR}}$) the volume of nanocrystalline in parts of the cores and the consistent core losses are little different. If the volume of the nanocrystalline part of the core is getting smaller then the current error decreases and the phase displacement rises.

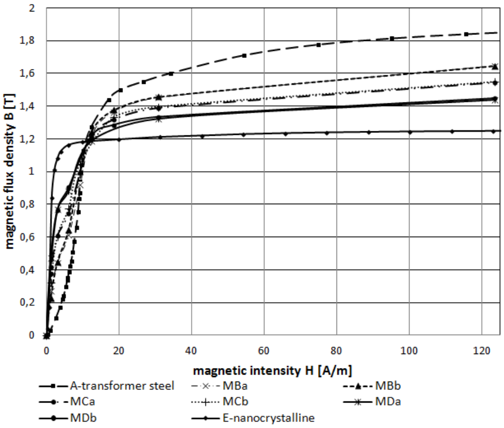



**Figure 10.** Equivalent magnetic characteristics of cores consisting of different proportions of two different connected magnetic materials (A, B, C, D, E) (total dimensions of core are constant) computed using the field-and-circuit method, (a) materials joined axially, and (b) radially.

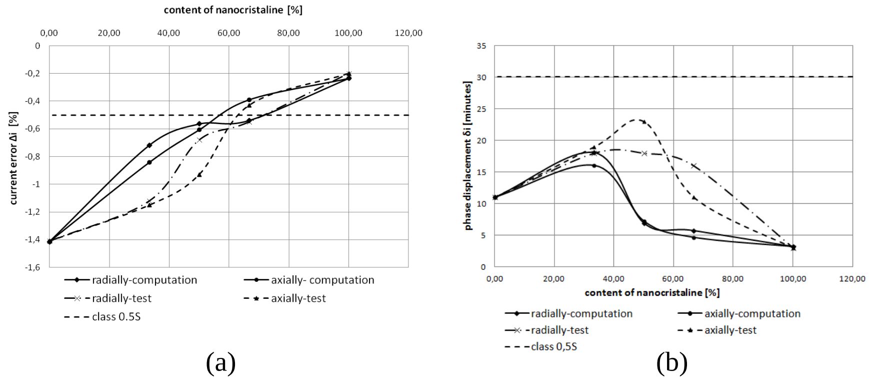



**Figure 11.** Comparison of the current errors and phase displacements for the current transformers with a core combined axially and radially vs. proportions of nanocrystalline in a joint, at the same load $S_n = 2.5\,\mathrm{VA}$, $\cos\varphi = 0.8$ ($I_{pn} = 100\,\mathrm{A}$).

Comments to Figure 11:

- The discrepancies between characteristics of cores connected in the different way have the same regularity for computations and tests (Figure 11).
- The current error is smallest for joined cores with higher contents of nanocrystalline material in core no matter how they are connected. In this case even small difference of volume causes the rise of core losses and current error. This situation appears in radially connected system — the volume of steel part is a little bigger and current error insignificantly rises.
- In case of lower contents of nanocrystalline material in core, magnetic flux concentrates in nanocrystalline part of the core and the magnetic flux density in steel are smaller in radially connected system. The core losses and current error are smaller than in axially connected system. It is result that the highest value of magnetic flux density is always near inner radius of the core and the nanocrystalline material has significantly lower lossiness [W/kg] than electrical steel.
- The discrepancies between computation and test are result of assumption that lossiness of material is constants in every point of this material. Values of lossiness are assumed on the basis of characteristic $p = f(B)$ for average magnetic flux density in electrical steel and nanocrystalline material. Therefore the discrepancies for case A (0% nanocrystalline material) and E (100% nanocrystalline material) are invisible. In real system lossiness are different in every point of the core and the core losses may be higher and measurement current error little bigger.

## 4. CONCLUSION

Research results show that the ways of connecting different magnetic material have no influence on measuring properties of measuring current transformers. The research was carried out on the assumption that the cross-section of both materials is the same in two types of connections. The measuring characteristics are very similar regardless of whether the core is connected axially (one-by-one) or radially (one inside the second). However proportions of steel and nanocrystalline material in a combined core are of great importance in measuring properties of measuring current transformers. The increase of nanocrystalline material in a core improves the measuring properties of the current transformer. The cost of a material however increases significantly.

Research carried out on real-life models and numerical models gave the same results. The constructor can not accurately predict the magnetic field distribution in different materials of the core and the application of the field-circuit method gives him the possibility to accurately determine the equivalent magnetic characteristics.

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