Toroidal HTS transformer with cold magnetic core - analysis with FEM software

B Grzesik, M Stepien and R Jez
Silesian University of Technology
B. Krzywoustego 2, 44-100 Gliwice, Poland
boguslaw.grzesik@polsl.pl, mariusz.stepien@polsl.pl, radoslaw.jez@polsl.pl

Abstract. The aim of this paper is to present a thorough characterization of the toroidal HTS transformer by means of FEM analysis. The analysis was a 2D/3D harmonic electromagnetic and thermal analysis. The toroidal transformer operated in LN2 by being immersed together with the magnetic core in it, for which its power losses were acceptable. Two extreme variants of windings were analysed. The first one called parallel and the second called perpendicular. Three variants of the magnetic core were considered. In the first one the core was put outside of the windings, in the second the core was inside of the windings and in the third variant the core was outside as well as inside of the windings. The windings were made of HTS tape Bi2223/Ag while the magnetic core was made of the nanocrystalline material Finemet. The two windings, with a 1:1 turn-to-turn ratio, were uniformly distributed along the whole torus circumference. The output power, efficiency and power density are in the results of the analysis. The temperature distribution was also calculated. In summary, the performance of the transformer is better than those currently known.

1. Introduction
The analyzed construction of the toroidal transformer is presented in Fig. 1 and Fig. 2. The two single layer windings with a 1:1 turn-to-turn ratio are uniformly distributed along the whole torus circumference. The 1:1 turn-to-turn ratio transformer is enough to build a transformer of almost any turn-to-turn ratio [1]. The windings have the shape of a helix with an angle that can vary from nearly zero to 90°. The magnetic core is put inside (not shown on figure) as well as outside. The windings are made of Bi2223/Ag HTS tape [2] while the magnetic core is made of nanocrystalline magnetic material [3]. This paper is a continuation of the authors’ works [4], [5].

The analysis is aimed at the following parameters of the transformer: i) input voltage, ii) input current, iii) output power iv) efficiency, v) power-to-mass ratio (P-t-M) and vi) temperature distribution.

The following assumptions were considered in the construction and analysis of the transformer: i) the dimensions of the transformer, which are determined by cryogenic facilities that will be used in future experiments (the height and the diameter of the cryogenic chamber is H=D=300 mm), ii) properties of the winding material (Bi-2223/Ag, *I*<sub>c</sub>=150A, *T*<sub>c</sub>=90K), iii) characteristics of the magnetic material (value of saturation of magnetic flux density *B*<sub>max</sub>=1.2 T, power losses, thermal conductivity) iv) the value of maximal voltage between windings (determined by the properties of Kapton insulation *U*<sub>max</sub>=800V), v) operation at 50 Hz and 77 K (cold magnetic core [6]), for which the transformer is designed.
The main dimensions of the transformer have been collected in Fig. 2.

![Figure 2. Dimensions of the transformer (mm)](image)

**Figure 1.** Toroidal HTS transformer

**Figure 2.** Dimensions of the transformer (mm)

The transformer core is based on the nanocrystalline soft magnetic material FINEMET. Its parameters were obtained during the investigation of the cryogenic temperature (LN$_2$ – 77K). These have been collected in Table 1, as well as in the hysteresis curve in Fig. 3.

| Parameter                          | Unit | Value       |
|------------------------------------|------|-------------|
| Chemical formula                   | -    | Fe$_{78.8}$Nb$_{2.6}$Cu$_{0.6}$Si$_{9}$B$_{9}$ |
| Temperature of the sample          | K    | 77          |
| Magnetic flux density of saturation $B_{\text{SAT}}$ at $H_{\text{MAX}}$ | T, A/m | 1.52 at 503 |
| Maximum operating point $H_{\text{MAX}}$, $B_{\text{MAX}}$ | A/m, T | 60; 1.2 |
| Magnetic permeability              | -    | 20 000      |
| Specific power losses              | W/kg | 0.36        |
| Thickness of the magnetic tape     | $\mu$m | 20         |

**Table 1.** Magnetic material – FINEMET at 50 Hz and 77 (K) (measured – Jun 06, 2007, 198/07/R – with REMACOMP-100 MAGNET PHYSIC GmbH)

![Figure 3. Hysteresis of FINEMET at 50 Hz and 77 K](image)

**Figure 3.** Hysteresis of FINEMET at 50 Hz and 77 K (measured – Jun 06, 2007, 198/07/R – with REMACOMP-100 MAGNET PHYSIC GmbH)

**2. Tubular transformer**

The tubular transformer, depicted in Fig. 4 and Fig. 5 is an approximation of the toroidal one, given in Fig. 1 and Fig. 2. Its main axis $O$ is a straight line. For its better visualization, only $\frac{1}{4}$ of the full model is presented. There are two extremely different realizations of the toroidal transformer. The first
one has turns of windings that are parallel to axis $O$ (Fig. 4) while the turns of the windings of the second realization are perpendicular to the main axis $O$ (Fig. 5). The tubular transformer has been analyzed as an approximation of the toroidal one. This has been done in order to find out if it is possible to characterize a toroidal realization by means of a 2D analysis of a tubular transformer. The first type of transformer is termed “parallel” and the second one “perpendicular” even though it is applied in the same way as the toroidal. The overall analysis of the tubular transformer as well as the toroidal one ranges from parallel (36 turns) to perpendicular (180 turns) through 11 helical cases. The data that characterizes the windings is given in Table 2 by means of three variables: i) shift (S), ii) number of turns (N) and iii) winding angle ($\alpha$). The first one (S) means the shift of the end of a single turn of winding relative to its beginning along the circumference. The second variable (N) has a standard meaning of the total number of primary/secondary turns. The winding angle ($\alpha$) is the angle between a turn of winding and the main axis of the toroid. Table 2 indicates what type of analysis was applied for the tubular model (tu) and for the toroidal model (to). The case of $S=0$, $N=36$, $\alpha=0$ refers to the parallel realization and the case of $S=180$, $N=180$, $\alpha=90$ refers to the perpendicular one.

### Table 2. Data concerning the windings and the type of analysis

| Shift (S) | 0    | 1    | 2    | 3    | 4    | 5    | 10   | 20   | 30   | 50   | 100  | 150  | 180  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Number of turns (N) | 36   | 39   | 44   | 49   | 55   | 63   | 72   | 86   | 116  | 174  | 178  | 179  | 180  |
| Winding angle ($\alpha$) | 0    | 8.1  | 15.9 | 23.2 | 29.8 | 35.7 | 55.6 | 72.0 | 78.5 | 83.9 | 88.1 | 89.5 | 90   |
| Type of electromag. analysis | tu   | 2D   | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2D   |
| | to   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   | 3D   |
| Type of thermal analysis | tu   | 2D   | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2D   |
| | to   | 3D   | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 3D   |

Analysis has been carried out for three variants of the magnetic core: a) 5 mm (thickness) for an external core, b) 25 mm (radius) for an internal core and c) 5 mm (thickness) for an external core together with a 25 mm (radius) of internal core. An additional analysis was done for the parallel variant with different thicknesses of the outer core ranging from 5 to a maximum of 60 mm (analysis done in step of 10 mm). All the variants of the analysis are also given in Fig. 7.

![Figure 4. Tubular parallel HTS transformer; axis O](image)
3. **ANSYS model of the transformer**

This section is devoted to the ANSYS models of the transformer as well as some additional information concerning the analysis of the transformer [7]. The models embrace an electromagnetic part and a thermal part, which is based on an electromagnetic one.

An electromagnetic phenomenon was analyzed with two types of model, 2D and 3D. Two variants of the 2D model were applied – one planar and one axisymmetrical. The planar one was used only for parallel realization, while the axisymmetrical variant was used only for perpendicular realization. For other shapes of windings, i.e., helical, the 3D model was built and applied. The 2D model allows one to get a fine mesh of finite elements in the regions where the spatial changes of the magnetic flux density are considerably higher. It allows for more accurate results to be obtained than in 3D analysis.

In order to ensure the accuracy, reducing the number of finite elements and decreasing the time consumption in 3D calculations the symmetrical model is applied [7]. The symmetry allows for the use of only 1/36 of the full model.

The transformer analysis was carried out at 50 Hz. The calculations are confined to a steady state with harmonic analysis.

The model of the transformer also reflects the model of superconducting winding. The HTS tape is modeled as the monocore type. This model of superconductor can be recognized as appropriate because the paper is focused on the properties of the HTS transformer. Hence, the phenomena in the micro scale (e.g. between filaments in HTS tape) are neglected. The resistivity of HTS tape is assumed to be 1E-12 Ωm.

The models characterize magnetic phenomena by parameters of nanocrystalline magnetic material. These parameters have been gathered in Table 1 and are depicted as the hysteresis curve in Fig. 3. Applied magnetic material has high performance that is confirmed by: high magnetic permeability $\mu_r=20000$, high magnetic flux density $B_{\text{max}}=1.2$ T, and very low specific power loses 0.36 W/kg. Its high permeability reduces the magnetic flux leakage and low specific power losses increasing the total efficiency of the transformer.

The thermal model has also been built for steady state analysis. Heat sources are calculated in electromagnetic analysis and applied to the HTS wires and the magnetic core. The temperature distribution is the result of analysis.

The transformer was analyzed using the FEM model with an ANSYS ver.12 package. A computer with an Intel Centrino 2GHz CPU and 3GB RAM was used for calculations. The influence of model size (number of finite elements) on the size of the database and the time of calculation is illustrated in Fig. 6.
4. Plan of analysis

The plan of the analysis is illustrated in Fig. 7. The characterization of the transformer is expressed by variables which are listed in Section 1 (Introduction), and are functions of the geometry and the parameters of the materials. Data concerning the analyses has also been gathered in Table 2.

5. Results of analysis

The results of the analysis marked in Fig. 7 have been gathered in five characteristics (Fig. 8 to Fig. 12). All of them have been calculated as a function of shift S. The shift S ranges from S=1 to S=180. These results are output power, efficiency, power density (power-to-mass ratio), input voltage and internal voltage drop.

They have been calculated as having one of the following quantities at a value equal to the limit (the magnitude of flux density 1.2 T or input current 100 A (rms)), while the second one is below the limit. This condition was taken into account for each value of S.

Analyzing Fig. 8 one can find that the output power at low shift S reaches high values in parallel realization like in the external core realization or in the external/internal one (3.9 kVA at S=1). Such realizations have the highest performance, which can also be observed in the efficiency and power density characteristics (power-to-mass ratio). They are depicted in Fig. 9 to Fig. 10 respectively. Parallel realization of the transformer has a power density of 590 W/kg, while the perpendicular one has 190 W/kg. If the current is increased to 120 A, the power density is 720 W/kg. Further increase of performance up to 800 W/kg can be obtained by increasing the thickness of the outer magnetic core.
A completely different value of output power is gained for the parallel realization with an internal core (0.04 kVA at S=1). Similarly, it results in low performance. In this case the magnetic flux density is close to zero. When the perpendicular realization (shift S=180), with an internal core, is considered the output power is the same as for the internal/external core. This means that the external magnetic core does not take part in energy transmission. The perpendicular realization, with an external core, operates at very low power and it behaves like a coreless transformer.

The power properties described above are confirmed by the characteristics of the input voltage and the internal voltage drop of the transformer. The shape of the first one (Fig. 11) is the same as the shape of the output power characteristics (Fig. 8). The parallel realization, with an internal magnetic core is unacceptable, because of the considerably high value of internal voltage drop. A similar situation occurs with the perpendicular realization, with only an external magnetic core. Both of the cases present behavior like that of a coreless transformer.
The thermal analysis was performed assuming a thermal steady state and an LN2 cooling (overcooled LN2 to 72 K). The transformer was loaded with heat sources calculated at an input current 100A (rms) and a maximum flux density 1.2 T. The results of the calculations are the temperature distributions. They are depicted in Fig. 13 and Fig 14.

Analyzing the temperature distribution in Fig 13 one can observe that the maximum temperature occurs in the internal magnetic core. The temperature decreases from the internal part of the transformer to the external surface. The temperature of the primary winding reaches 72.3 K. For an internal core, the temperature is constant and lower than in the case of a perpendicular core – Fig. 13b. The temperature for parallel realization is illustrated in Fig. 13b. The temperature is highest in the middle of the internal core because of the power losses generated in it. The details of temperature distribution along the radius of the torus (from inside to outside) is depicted in Fig. 14.

**Figure 13.** Temperature distribution for parallel (a) and perpendicular (b) realization

**Figure 14.** Temperature distribution along torus radius (inside to outside)
6. Remarks concerning technology of fabrication
The fabrication of the transformer is a technological challenge, especially the fabrication of the windings in the parallel realization. It creates considerable difficulties. They stem from the fact that it is impossible to put a 1G flat tape of superconductor on the torus to form a toroidal helix with full contact. The flat tape of superconductor can only be formed as a toroidal helix by stretching and bending it properly, but such deformations can damage the superconductivity of the HTS tape. Using the narrow 2G (coated conductor) tape is a partial remedy [8], but the best possible solution is 2G deposited onto the torus in the form of a helix. Nevertheless, the latter solution needs advanced technology.

7. Conclusions
i) The analyzed transformer of the parallel realization exhibits better performance (590 W/kg) than the perpendicular one (190 W/kg). If the current is increased from 100 A to 120 A, the power-to-mass ratio is 720 W/kg. It is possible to increase the thickness of the magnetic core, which results in approx. 800 W/kg.

ii) The maximum efficiency 99.8 % was obtained by a parallel realization.

iii) Because the temperature of the transformer can exceed 77 K, it is necessary to use overcooled LN2. This is why the thermal analysis was performed for LN2 at 72 K.

iv) The coated conductors are the only solution for parallel realization of the transformer because it is impossible to put 1G HTS tape on a torus that would be at a tangent at least in each of its middle points to the torus.

v) Also a one-to-one turn-to-turn ratio transformer is acceptable because it is possible to arrange any turn-to-turn ratio using this one-to-one solution.

vi) The laboratory investigation will be performed as a continuation of this work.

References
[1] Grzesik B., Bodzek K., Stepień M.: Modular transformer with any turn-to-turn ratio, Electronics (Faculty of Electrical Engineering Univ. of Banjaluka), Vol. 9, Number 2, pp. 40-44, Dec. 2005
[2] American Superconductors Web Page, http://www.amsc.com/
[3] Institute of Non-ferrous Metals In Gliwice POLAND, http://en.imn.gliwice.pl/
[4] Grzesik B., Jeż R.: Highly efficient HTS-transformer requires low power losses, 14th International Symposium on Power Electronics, Ee2007, 7-9.11.2007, Novi Sad, Serbia.
[5] Grzesik B, Janowski T., Stepień M.: HTS Toroidal Helical Transformer, Journal of Physics: Conference Series, Article no. 012311 Vol. 97, 2008.
[6] Tixador P.: Transformers & SMES, European Summer School on Superconductivity, Pori, Finland, June 11-18, 2008.
[7] ANSYS Documentation Release ver. 12.0.
[8] Tixador P.: Advances in HTS Materials, WAMSDO Proceedings, 2009.