HTS Toroidal Helical Transformer

B Grzesik¹ T Janowski² and M Stepien³

¹, ³ The Silesian University of Technology
B. Krzywoustego 2, 44-100 Gliwice, Poland
² Lublin Technical University
Nadbystrzycka 38a, 20-618 Lublin, Poland

¹boguslaw.grzesik@polsl.pl; ²t.janowski@pollub.pl ³mariusz.stepien@polsl.pl

Abstract. The paper describes novel HTS toroidal transformer with helical windings, operating at 50 Hz. The turns of outer winding are parallel to turns of inner one. This arrangement of windings results in the same length and shape of each turn. The latter ensures homogeneous distribution of flux density. The magnetic core, in turn, improves coupling between windings, giving at the same time homogeneous magnetic flux distribution in windings. Proposed shape of windings reduces perpendicular component of flux density in HTS wires. It allows for the best possible utilisation of the HTS wire. The transformer has the magnetic core cooled with LN2. The transformer has turn-to-turn ratio 1:1 as it is designed for modular system. Its windings are made of Bi²Sr²Co²Cu³Ox wire. Material of magnetic core has accepted power losses in LN2. The magnetic core is also kept in ambient temperature. Thorough analysis of proposed HTS transformer will be carried out using Finite Element Method (FEM) and measurements resulting in critical current, rated power density and rated efficiency. The circuit model of the transformer is also given.

1. Introduction
Significant increasing of power density in power transformers is possible using HTS windings of transformer. Now known solution of HTS transformer operates with power density two times greater than conventional one (at the same power volume and mass of transformer are decreased). While windings of HTS transformer are made of Bi²Sr²Co²Cu³Ox tape, critical current of windings wire depends on magnetic field shape. Majority of known HTS transformers have windings made of stacked pancake coils. It gives good results at middle part of windings but critical current of external pancakes is considerably smaller than critical current of middle coil pancakes. Because of serial connections external pancakes limit critical current of whole coil. Novel shape of coil, where magnetic field has the same orientation to each wire of windings, allows better utilization of HTS wire, because critical current is the same in each turn of coil.

2. Motivation
The transformer with possible power density made of HTS windings and magnetic core operating at liquid nitrogen is the motivation of this work. Windings of transformer made of BiSCCO-2223 tape needs proper design to obtain high current density. Magnetic core needs proper magnetic material with acceptable power losses at low temperatures (especially at LN2). Authors are looking for transformer with better as possible utilization of HTS wire and simple cooling system (whole transformer in LN2).
3. HTS transformers – review of previous works
Development of HTS BiSCCO wire caused intensive research on HTS electrical machines and transformers [1]. Many works were focused on transformers [1] – [6], [10]. Special attention was given to the utilization of HTS wire the critical current that strongly depends on magnetic flux density, especially its perpendicular component. Works [1], [2] and [5] are good and representative examples how to reduce perpendicular component of magnetic flux. In [1] and [2] authors applied diverters while in [5] the special arrangement of low current density coils were investigated. Both solutions results in effective reduction of the undesirable perpendicular component of magnetic flux density. The another possibility of reduction of perpendicular component of magnetic flux density, such as is proposed in this paper has not been reported so far. Therefore authors has undertaken research work to examine details of this new solution.

4. Design of transformer
The HTS transformer proposed in the paper is depicted in figure 1. It is made of HTS windings and amorphous magnetic core. has turn to turn ratio 1:1. The transformer is devoted for modular arrangement. Only single module of the transformer is taken into consideration in this paper.

![Figure 1. HTS helical transformer](image)

Winding of the transformer has windings where each turn is helically shaped. The turns of primary winding are parallel to secondary ones. Both of windings are distributed on torus surface. This arrangement gives high coupling coefficient of windings. Cross-section of the transformer with detailed cross-section of winding turns is depicted in figure 2.

Windings of the transformer are made of BiSCCO-2223 High Strength Plus Wire [8] with Kapton insulation. Windings are placed on epoxy glass former and fixed by epoxy resin. Critical current of HTS wire is 145 A. Magnetic core cylindrical in shape is placed outside of windings and it is made of thin tape of amorphous alloy Metglas 2605SA1 [9] wrapped around transformer windings. The magnetic material is characterized by very high magnetic permeability (~20 000) and relatively low power losses (~1.5 W/kg at 77 K) and magnetic field saturation of 1.5 T.

5. Basic dimensions and rating data of proposed transformer
The dimensions of basic transformer described in this paper are shown in figure 3. The dimensions are set due to technological possibilities of fabrication of experimental transformer. It was limited by bending radius of HTS wire and by saturation field of magnetic core. Each winding of transformer is made of 31 turns. Total length of wire in single winding is approximately 20 m. The magnetic core of the transformer is made of 30 rings (made of Metglas tape) with total weight around 2.3 kg.
The transformer characterized by dimensions from figure 3 was analyzed by Finite Element Method using 2D model and harmonic analysis. Results of analysis are ratings of transformer obtained under following assumptions:

- Critical current not exceed 80 A (critical current calculated from parallel component of magnetic flux density in HTS wire)
- Maximum of magnetic flux density in magnetic core is below 1T (magnetic core operates at linear part of B-H curve)

Results of transformer analysis are as follows: i) supplying voltage 23 V, ii) output power 1.9 kW, iii) power density 0.6 kW/kg, iv) estimated power losses 4W (AC losses in HTS wire are not included), v)estimated efficiency (excluding losses in cooling system) 99.79 %

Important advantage of transformer are flux lines that are parallel to longer side of wire cross-section. Magnetic flux lines near HTS wires are shown in figure 4 and distribution of magnetic flux density in wire is shown in figure 5. The x-direction component (perpendicular component) of flux density has very low value, about 0.007 T that is negligible.
6. Influence of magnetic core on transformer properties

Properties of the transformer depend on magnetic core. Firstly, it depends on temperature of magnetic core. One of variants of the transformer operates with magnetic core in room temperature while other in LN2 therefore it was necessary to carry out an analysis of influence of the distance between windings and magnetic core on magnetic properties of the transformer. When magnetic core operates at room temperature it needs thermal insulation inserted in between magnetic core and windings. It increases distance between core and windings. The properties of the transformer as a function of this distance is described in details in Subsection 6.1. Secondly, thickness of magnetic core influences on transformer properties. Subsection 6.2 describes this dependence in details.

6.1. Influence of distance between windings and magnetic core on transformer properties

Magnetic core separated from windings by thermal insulation at the same operation conditions of transformer generates higher power losses because flux density increases. Distribution of magnetic flux density at three different distances between magnetic core and windings is depicted in figure 6. Additionally characteristic of maximum flux density vs. distance is shown in figure 7.
6.2. Influence of thickness of magnetic core on transformer properties
Increasing of thickness of magnetic core decreases maximum flux density but volume and weight of magnetic core increases strongly (power density is considerably decreased) – figure 8. Optimum thickness of core is for maximum value of flux density near saturation. According to flux density distribution depicted in figure 9 and maximum flux density vs. thickness 5 mm thickness was chosen for further consideration.

**Figure 7.** Maximum flux density versus distance between windings and magnetic core

**Figure 8.** Distribution of magnetic flux density (in T) at different thickness of magnetic core, a) 5 mm, b) 10 mm, c) 15 mm
7. Conclusions

Novel solution of HTS transformer directed to elimination of perpendicular flux density component was described and preliminary analyzed in this paper. Transformer has helically shaped windings and whole operates at LN2 temperature. Magnetic core immersed in LN2 generates higher losses than in room temperature but gap for thermal insulation causes higher power losses due to higher value of flux density. Efficiency of transformer (calculated by FEM) is very high (99.97% excluding losses of cryogenic part). The only drawback is technology of fabrication of the transformer. Advanced shape of windings needs very careful winding process and it is difficult to automatic production. Additionally fabrication of magnetic core needs disassembled design because it is mounted on windings after winding process.

References

[1] Sykulski J, Goddard K and Stoll R, 1999 IEEE Trans. on magnetics 35 3559 – 3561
[2] Jelinek Z et al., 2003 IEEE Trans. on Applied Superconductivity 13 2310 – 2312
[3] Wang Y S et al., 2004 IEEE Trans on Appl. Superconductivity 14 924 – 927
[4] Tixador P et al., 2005 IEEE Transactions on Applied Superconductivity 15 1847 – 1850
[5] Seok B Y and Lee C J, 2005 IEEE Trans. on Applied Superconductivity 15 1871-1874
[6] Reis C T et al., 2002 IEEE Power Engineering Society Winter Meeting 1 151 - 156
[7] ANSYS Documentation Release 10.0
[8] American Superconductor Web page documentation
[9] Hitachi Metals Ltd. Web page documentation
[10] Tixador P, Dornnier-Valenitin G and Maher E 2003 IEEE Trans on Applied Superconductivity 13 2331-2336