Toroidal superconducting transformer with cold magnetic core - results of analysis and measurements

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Abstract. The paper is focused on a toroidal superconducting transformer with cold magnetic core. The transformer was developed aiming at the solution where magnetic core could operate immersed in LN2, not having much higher power losses than a core operating in room temperature. The second aim is concerned to the perpendicular component of the magnetic flux. It was assumed that it should be minimized. The third aim is required maximal coupling coefficient between windings. Magnetic material METGLAS 2605 SA1 (Metglas Ltd) was selected as the best taking electrical and mechanical properties into account. Numerical analysis of the transformer was carried using ANSYS software. It was assumed that magnetic core could be put inside windings and/or outside of it. The analysis and measurements yield that the best solution is the transformer with magnetic core put inside the windings. Such a construction reduces significantly perpendicular component of the magnetic field in HTS wire. Because outer winding is put on the inner one it gives maximal possible coupling coefficient. The primary and the secondary have the same number of turns. It means bifilar way of winding. The described transformer has the following constructional data: i) diameter of the main circle: 144 mm, ii) maximal diameter: 208 mm, iii) diameter of the small cross-section of the transformer (without external magnetic core): 50 mm and it results with the following parameters: output power 1.59 kVA, power density 700 VA/kg, efficiency: 99.5, coupling coefficient 0.99 at 100 A_{RMS} of input current and maximum flux density 1.2 T.

1. Introduction
A transformer is one of the most important elements in the electric power system. The efficiency of the transformer influences on the efficiency of the whole power system. Application of new materials (HTS conductors, amorphous magnetic materials) increases the efficiency of the transformer. The paper contains the results of modeling and laboratory tests of HTS transformer with amorphous magnetic core that is kept in LN2 [1, 2, 3].

The idea of analyzed toroidal HTS transformer is presented in Fig.1. The windings of the transformer are uniformly distributed along whole torus circumference with 1:1 turn-to-turn ratio. The windings are made of HTS tape Bi-2223. The cold magnetic core (in LN2) is made of amorphous magnetic material METGLAS 2605SA1. The windings have the form of helix with the angle that can vary from near zero to right one. Magnetic core is put inside (not shown in Fig.1) as well as outside of the windings. The presented HTS transformer was theoretically analyzed by FEM for different variants of construction (only internal magnetic core, only external magnetic core and both types of magnetic core for various angles of windings). A transformer with internal core, similar to the classical toroidal transformer, was examined in laboratory. The results are presented in this paper.
2. An experimental toroidal transformer

The described toroidal HTS transformer was one variant of mentioned (see Fig. 1) where magnetic core is put inside windings. The windings are perpendicular to the main axis of the transformer. This is a typical construction of the transformer with toroidal shape of the magnetic core and copper windings.

The construction of the experimental HTS transformer is presented in Fig. 2. The internal magnetic core is made of amorphous tape of METGLAS 2605SA1 and put into the toroidal former. It is made of epoxy resin reinforced by glass fiber. The HTS windings are uniformly distributed in one layer on the spool of the transformer. The primary winding containing 65 turns forms the inner layer while the secondary having the same number of turns - 65 forms outer layers. The distance between them equals twice of Kapton's thickness. The isolation (1 000 V) between primary and secondary winding is made of Kapton tape.

3. A stand for laboratory tests

The scheme of the laboratory stand is presented in Fig.3. The experimental HTS transformer was immersed into LN2 in the open cryostat. The transformer was supplied by the current source with adjustable range of amplitude and frequency of the output current (10 - 100 A; 40 - 71 Hz). The transformer was measured by digital oscilloscope Tektronix TDS 3032 with current probes (Chauvin-Arnoux) and voltage probes (Tektronix P5205).

The stand was used to carry out measurements of the transformer. A results of the laboratory tests embrace the main parameters of the transformer and parameters of the equivalent circuit. During the tests the input and output voltages \( u_1(t), u_2(t) \) and the input and output currents \( i_1(t), i_2(t) \) were measured in the wide range of current value (10A - 100A) and current frequency (40 - 71 Hz).
4. Results of numerical modelling of toroidal transformer

A detailed numerical analysis was carried out using 2D and 3D ANSYS modeling. Assuming linear parameters of model (harmonic analysis) and HTS wire operated with rated current power properties were determined. The results were calculated for different shift $s$ angle, which reflects twist of HTS wire (shift $s$ is 0 at windings parallel to core axis – normal to core cross section, and it is 180 when windings are perpendicular) – cf. Fig. 5. In Fig. 5 output power is shown as a function of shift $s$.

The perpendicular transformer (with shift $s$ 180) is corresponding to the experimental one. The results obtained for this type are input voltage 13.5 V, output power 1340 VA (cf. Fig. 5), efficiency 99.5% and power density 194 VA/kg.

5. Results of laboratory tests

The results of the laboratory tests embrace the main parameters of the transformer and parameters of the equivalent circuit. During the tests the input and output voltages $u_1(t)$, $u_2(t)$ and the input and output currents $i_1(t)$, $i_2(t)$ were measured in the wide range of current value (10A - 100A) and current frequency (40 - 71 Hz).

The results of the tests: no-load and short circuit, were used to determine the parameters of the equivalent circuit of the HTS transformer. The scheme of the equivalent circuit is presented in Fig. 6. The parameters $R_1$, $R_2$ ($L_1$, $L_2$) represents correspondingly: the resistance (leakage inductance) of primary and secondary HTS winding. The parameters $R_{Fe}$ and $L_m$ represent the power losses and magnetizing reactance of the magnetic core. The parameters $C_{11}$ and $C_{22}$ represents the stray capacitance of the primary and secondary winding while the parameter $C_{12}$ represents the stray capacitance between primary and secondary layer of winding. A values of the parameters of equivalent circuit are shown in Fig. 6.

The load tests were used to determine the efficiency $\eta$, power-to-mass ratio $P$-t-m and power losses $\Delta P$ of HTS transformer for given input parameters as voltage $U_1$, current $I_1$, power $S_1$ and frequency $f$. The results are collected in Tab. 1. Because of low power losses the transformer has high efficiency and high power-to-mass ratio for different frequencies of the input current.
Table 1. Power properties of the transformer (measured).

| frequency $f$ (Hz) | 40 | 45 | 50 | 57 | 61 | 66 | 71 |
|---------------------|----|----|----|----|----|----|----|
| input voltage $U_1$ (V) | 12.5 | 14.1 | 15.4 | 17.8 | 19.1 | 20.5 | 22.2 |
| input power $S_1$ (kVA) | 1248 | 1411 | 1540 | 1776 | 1914 | 2052 | 2224 |
| efficiency $\eta$ (%) | 99.46 | 99.48 | 99.49 | 99.53 | 99.56 | 99.57 | 99.60 |
| power-to-mass ratio $P-t-m$ (VA/kg) | 574 | 648 | 709 | 815 | 880 | 940 | 1024 |

Figure 6. Equivalent circuit of the transformer and its parameters.

The transformer described in the paper having only one layer primary and one layer of secondary has power-to-mass ratio ($P-t-m$) of ~700 VA/kg that is higher value in comparison with reported one. For the transformer with higher number of layers one can obtain much higher than 700 VA/kg what makes it candidate for higher power and voltage construction.

6. Conclusions

The presented toroidal HTS transformer with cold magnetic core is made of new materials: HTS tape Bi-2223 and amorphous magnetic core METGLAS 2605SA1. It exhibit low power losses, high efficiency and high power-to-mass ratio ($P-t-m$) of ~700 VA/kg. The parameters of HTS transformer compared with other constructions of HTS transformer described in the literature [4, 5, 6].

The future work will be focused on the increasing the output power of the transformer and increasing its voltage. It can be achieved by changing the turn-to-turn ratio and operation in lower temperatures than 77K (increasing the critical current of HTS tape). The future works will embrace also voltage brake problems.

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