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13,8 kVA transformer with windings made of YBCO HTS tapes

Streszczenie. *W pracy przedstawiono konstrukcję jednofazowego transformatora z uzwojeniami wykonanymi z taśmy nadprzewodnikowej drugiej generacji. Wykreślono uzyskane z pomiarów charakterystyki stanu jałowego pracy i stanu zwarcia pomiarowego transformatora. Podano wartości impedancji zwarcia i jej składowych oraz starty mocy. We wnioskach końcowych podano uwagi do projektowania transformatorów nadprzewodnikowych oraz konkluzje wynikające z ich eksploatacji. (**Transformator o mocy 13,8 kVA z uzwojeniami wykonanymi z taśmy nadprzewodnikowej YBCO**).*

Abstract. *This paper presents the design of one-phase transformer with the windings made of second generation of HTS tapes. The no-load operation and transformer short-circuit measurement characteristics were deleted from the measurements. The values of short-circuit impedance, its components and power losses were specified. In closing remarks comments were made on the designing of superconductor transformers and operational conclusions.*

Słowa kluczowe: transformator, nadprzewodnictwo, taśma nadprzewodnikowa.
Keywords: transformer, superconductivity, HTS tapes.

Introduction

The first attempts to design superconductor transformers were taken in 1960s, when superconductors, at that time still low temperature, became easily available. High prices of superconductors and necessity to cool them down to temperature of 4.2K led to economic and technical problems. These problems were limited by the discovery of high temperature conductivity in 1986. At present the superconducting transformers are one of the most promising applications of superconductors [1] [2].

The most useful property of superconductors, from the perspective of their use in transformer windings, is the ability to conduct high currents at very low power losses [3]. The replacement of the conventional transformers in the power grid with superconducting transformers allows to reduce transmission losses by more than 60%. Small sections of HTS tapes allow to design coils with smaller axial and radial dimensions than in the case of applying copper winding wires. This translates into smaller dimensions of transformer core, and consequently the smaller outside dimensions and smaller weight [4] [5].

A disadvantage of superconducting transformers are manufacturing costs, which are several times higher. Extremely high costs of failure removal in case of superconducting transformers force the designers to face extremely high requirements on the design correctness and assembly quality as well as protection system reliability, its sensitivity, response time and selectivity in detection of failure conditions. A major operational problem of the superconducting transformers is a requirement to maintain windings at the cryogenic temperature and not to allow for superconductivity losses.

This paper presents the design of one-phase 13.8 kVA transformer with the windings made of second generation of HTS tapes. The measurements were taken and the characteristics of the no-load condition and characteristics of the transformer's measuring short-circuit characteristics were provided. The specified power losses comprise load losses, iron losses and total losses. In closing remarks comments were made on the transformer design and operational conclusions were drawn.

Superconductivity

A basic feature of superconductors that makes them different from the group of electricity conductors is a decline of their resistance to nil once they have been cooled down to a certain critical temperature T_c [6] [7]. A simplified transition characteristics is presented in Figure 1.

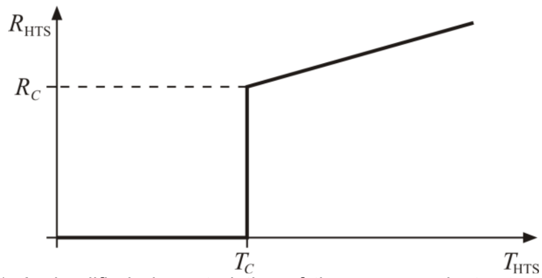

Fig. 1. A simplified characteristics of the superconductor transition [6] [7]

Another characteristic feature of the superconductors is the Meissner-Ochsenfeld effect. Once the superconductor has been cooled down to the temperature lower than critical, the external magnetic field does not penetrate its interior. However, once a certain critical threshold value of the magnetic field strength H_c is exceeded the superconductivity fades away. The superconductivity fading causes also sufficiently strong magnetic field, which is a derivative of the strength of electric current conducted by the material in compliance with the Maxwell equation. If a certain threshold value of critical current density J_c has been exceeded, the superconductivity fades away.

Density of critical current J_c, critical temperature T_c and critical magnetic field strength H_c are parameters specific to the superconducting materials. These parameters, expressed in absolute terms, determine the critical surface of the superconductor (Fig. 2) [6] [7].

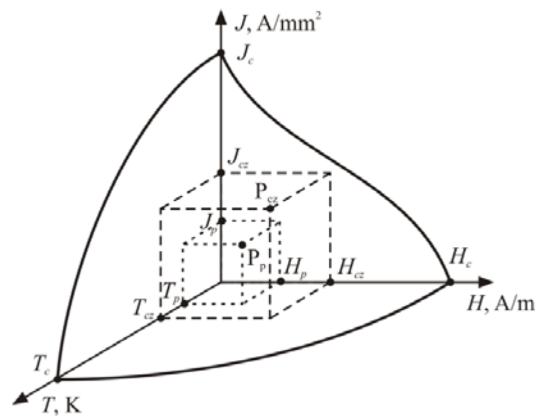

Fig. 2. Critical surface of the superconductor [6] [7]

The actual values of critical parameters of the superconductor T_{cz}, H_{cz}, J_{cz} are lower than the critical parameters T_c, H_c, J_c in absolute terms (Fig. 2). The differences are determined by the spot on critical surface where the operational point of superconductor P_{cz} was selected. It is possible to maintain the material superconductivity only and exclusively when the values of its temperature T_p, external magnetic field strength H_p and density of current conducted through the material J_p have lower values than the critical actual values T_{cz}, H_{cz}, J_{cz} i.e. when the operational point P_p is located underneath the critical surface (Fig. 2).

Transformer design

In order to gain design and operational experience a one-phase 13.8 kVA transformer was constructed, with the high voltage (HV) and low voltage (LV) of the transformer made of second generation HTS tapes. A photo of transformer in operational order is shown in Fig. 3.

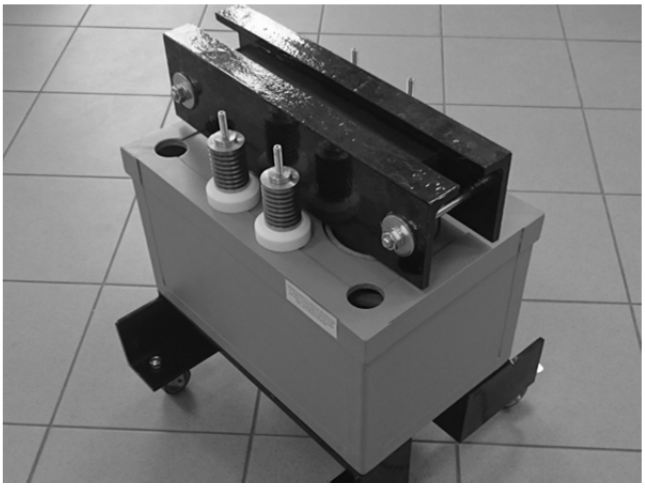

Fig. 3. 15 kVA superconducting transformer

The nominal data of transformer is specified in Table 1. The transformer was designed with high voltage (HV) of 230 V and low voltage (LV) of 60 V. The rated current on the HV side is 60 A, and on the LV side - 230 A. The induction in the core is 1.6 T. The percentage short-circuit voltage equals 3.2%.

Table 1. Transformer's nominal data

Power	13.8 kVA
Frequency	50 Hz
HV/LV winding voltage	230 V/60 V
HV/LV winding current	60 A/230 A
Magnetic induction	1.6 T
No-load current	0.7 A
Short-circuit voltage	3.2%

Outline cross-section showing transformer design is shown in Fig. 4.

The transformer design contains a core made of electrical sheet compliant with the EN10107:2005 standard. Material marking M105-30S. Sheet thickness is 0.3 mm. Silicon content approx 3%. Sheet maximum total loss at 50 Hz and induction of 1.5 T is 0.97 W/kg and 1.5 W/kg at 1.7 T. The minimum magnetic induction for this sheet is 1.75 T, at the magnetic field strength equal to 800 A/m. The core is stepped, containing 4 steps and is spliced at the angle of 45° with the sheet cutting layout: 4, 3, 1.

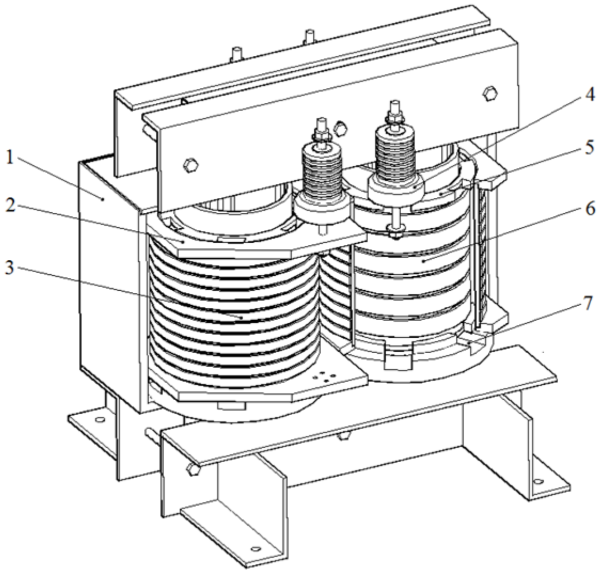

Fig. 4. Outline cross-section of the design: 1 - cryostat, 2 - HV carcass, 3 - HV winding, 4 - bushings current, 5 - LV carcass, 6 - LV winding, 7 - cooling ducts

The windings were made of second generation HTS tapes manufactured by an American company SuperPower Inc. The HV windings were made of the tape with the manufacturer's symbol SCS4050-AP with the minimum critical current of 87 A, at temperature of 77K and in own field. The LV winding was made of tape with Ref. No. SCS12050-AP, with the minimum critical current of 333 A.

The design of tapes is presented in Fig. 5, whereas Table 2 specifies parameters for individual layers. In both tapes the superconductor used is ReBCO i.e. Barium - Copper Oxide. The tapes have the identical thickness of 0.1 mm, however, their width is different. The SCS4050-AP tape is 4 mm wide, whereas the SCS12050-AP tape is 12 mm wide.

To make windings 46.6 m of the SCS4050-AP and 9.7 m of the SCS12050-AP tape was used. Total number of HV and LV windings was divided into two coils with the identical number of windings. In case of HV winding there are two (2) coils with 42 windings, and in case of LV winding there are two (2) coils with 11 windings. The HV and LV coils are co-axial and are founded on both core columns.

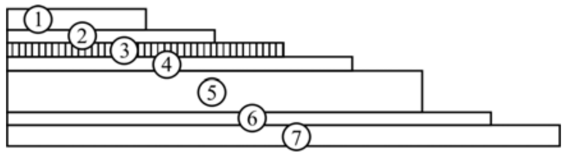

Fig. 5. Structure of SCS tape made by SuperPower Inc.

Table 2. Structure of SCS tape

Layer No.	Thickness	Material	Resistivity 20°C	Temperature coefficient of resistance
1	20 μm	Copper	$1.72{\cdot}10^{-8}$ Ω·m	$3.9{\cdot}10^{-3}$ K^{-1}
2	2 μm	Silver	$1.59{\cdot}10^{-8}$ Ω·m	$4.1{\cdot}10^{-3}$ K^{-1}
3	1 μm	(Re)BCO	–	–
4	1 μm	Buffer zone	–	–
5	50 μm	Hastelloy C-276	$1.26{\cdot}10^{-6}$ Ω·m	$1.3{\cdot}10^{-4}$ K^{-1}
6	1.8 μm	Silver	$1.59{\cdot}10^{-8}$ Ω·m	$4.1{\cdot}10^{-3}$ K^{-1}
7	20 μm	Copper	$1.72{\cdot}10^{-8}$ Ω·m	$3.9{\cdot}10^{-3}$ K^{-1}

The windings parameters are specified in Table 3. The resistance of the HV winding is $0.0466 \cdot 10^{-18}$ Ω in the superconductivity condition and $23 \cdot 10^{-6}$ Ω in resistive condition at the temperature of 77 K and 2.9 Ω at 293 K. The resistance of the LV winding is $0.0097 \cdot 10^{-18}$ Ω in the superconductivity condition and $5 \cdot 10^{-6}$ Ω in the resistive condition at 77 K and 0.57 Ω at 293 K.

Table 3. Windings parameters

No. of HV/LV windings	84/22
HV /LV winding material	Super Power (Re)BCO SCS4050-AP /SCS12050-AP
Dimensions of HV /LV winding wires	0.1×4.0 mm /0.1×12.0 mm
Length of HV/LV winding wires	46.6 m/9.7 m
Resistance of HV/LV windings (at 293K)	2.9 Ω/0.57 Ω
Resistance of HV/LV windings (at 77K)	$0.0466 \cdot 10^{-18}$ Ω /$0.0097 \cdot 10^{-18}$ Ω
HV/LV winding resistance after transition into resistive condition (77K)	23 μΩ/5 μΩ
Inductance of HV/LV windings	290 μH/18 μH

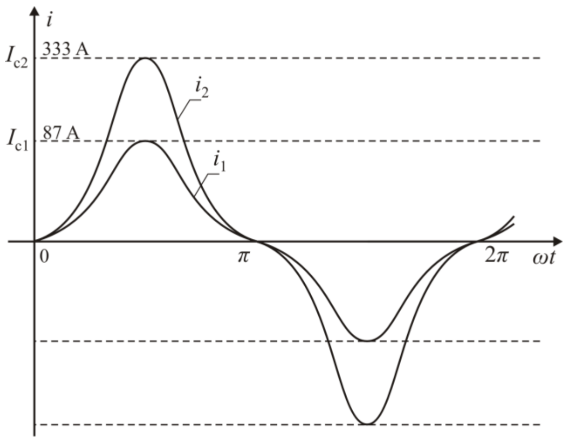

Fig. 6. Current transformer at rated load

When designing superconducting transformer the economical use of HTS tapes has to be born in mind, because they are an expensive material. It is not economical to apply HTS types with critical current significantly exceeding rated currents of the transformer. For the presented design the ratio between critical value of the HV winding current to the rated value of the same winding is 1.44, which is a square root of two. The same value has the ratio of critical value of LV winding to the value of rated current of the same winding. This implies that during transformer operation with rated load the maximum values of current in HV and LV windings are equal to the critical values of the windings, as shown in Fig. 6.

The windings are fixed on carcasses made of epoxy and glass composite resistant to cryogenic temperatures (Fig. 7). To provide appropriate cooling of windings the carcasses are equipped with distributed cooling ducts, in which circulates liquid nitrogen. The carcasses with windings are fixed to the cryostat. The cryostat is made of the same composite material as carcasses, however, the difference is that it was strengthened with Honeycomb aramid spacing material. It has two wall separated with thermal insulation. The superconducting windings go out of the cryostat via bushing current. The bushings current were made of ribbed copper shafts.

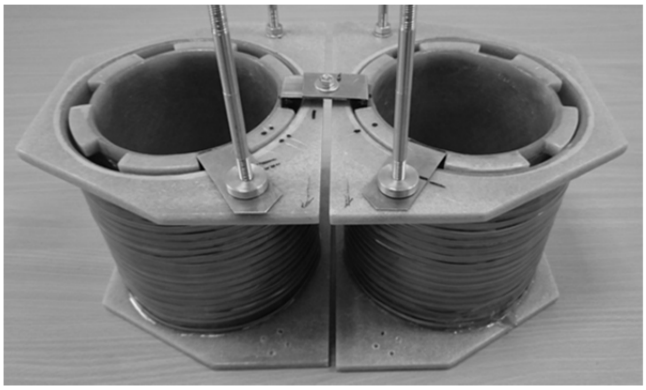

Fig. 7. Windings in carcasses

The transformer core is located outside cryostat and operates at the atmospheric temperature. It is not economically viable solution to cool core with liquid nitrogen. The losses in iron are slightly lower at cryogenic temperature, which does not compensate energy losses born to cool the core.

Transformer measurements

The transformer measurements were taken in two operational conditions: when transformer had no-load status and measuring short-circuit status. The no-load status characteristics are presented in Fig. 8.

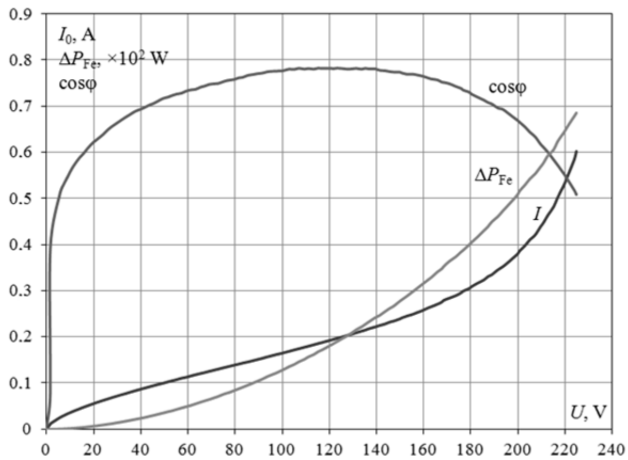

Fig. 8. The characteristics of no-load status of 13.8 kVA transformer

When rated voltage is supplied the current off-taken by the transformer from the power grid is 0.7 A, whereas active power consumed by transformer is 71 W, and power factor cosφ equals 0.48.

The measuring short-circuit characteristics are presented in Fig. 9. The transformer short-circuit voltage is 7.3 V, which accounts for 3.2% of the rated voltage. The active power measured in measuring short-circuit condition equals 197.9 W.

The taken measurements and calculations showed that the short-circuit impedance of the transformer is 120.6 mΩ. Meanwhile the short-circuit resistance equals 53.5 mΩ, whereas short-circuit reactance equals 108.1 mΩ (Table 4).

Total power losses equal 265.8 W, whereas the iron losses equal 67.9 W, whereas the load losses equal 197.9 W (Table 5). Thus, the load losses account for 75% of the total losses.

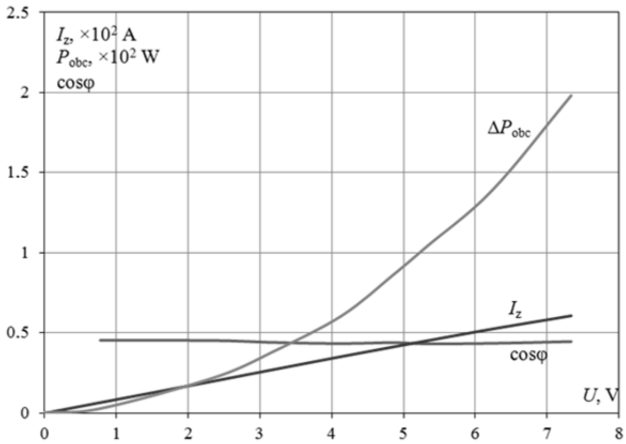

Fig. 9. The characteristics of no-load status of 13.8 KVA transformer.

Table 4. Short-circuit impedance and its components

Short-circuit impedance, Z_z	120.6 mΩ (77K)
Short-circuit resistance, R_z	53.5 mΩ (77K)
Short-circuit reactance, X_z	108.1 mΩ (77K)

Table 5. Power losses

Load losses, ΔP_{obc}	197.9 W
Iron losses, ΔP_{Fe}	67.9 W
Total losses, P	265.8 W

Conclusions

The constructed transformer has positively passed the operational tests in no-load and short-circuit measuring conditions. Further tests will include operation in load and overload conditions, in the short-circuit condition at the rated voltage and inrush current will be tested.

In the designed transformer, in rated load condition, the maximum value of HV and LV winding current overlaps with the values of critical winding currents. This implies that even during small transformer overload the current critical values will be exceeded and windings will undergo transition from the superconductivity into resistive condition. Thus the values of rated currents, in the HV and LV windings, have to be selected in the manner allowing to retain safety margin in case of transformer overload. In case of the transformer in question the rated current values have to be reduced down to 54 A in the HV winding and to 209 A in the LV winding i.e. to reduce transformer power to 12.4 kVA. This gives 10% safety margin for current increase in case of transformer overload. The reduction of transformer power gives also safety margin for fluctuations of the superconductor critical parameters, translating into change of the position of operational point selected on the critical surface.

A major issue, not analysed so far, is related to the occurrence of transformer short-circuit condition. As a consequence the superconducting windings will conduct current with the value several times higher than the critical value of the superconductor. Thus one has to take into consideration the loss of superconductivity of windings, which given the underperforming cooling system, may lead to thermal damage of HTS tapes. Similar effects may be caused by the inrush current during transformer connection to the supply grid.

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