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YBCO coated conductors for superconducting transformer windings

***Abstract**. Contemporary technology permits for the construction of superconducting transformers with windings made of high-T_C superconductor coated tapes (2G HTS tapes). The main problem is the cost of superconducting material and cryogenic cooling. In this paper, authors try to evaluate the influence of the transformer parameters over the superconductor working conditions and thereby over the total quantity of HTS tape used for transformer windings. Presented in this paper calculations was made for the three-phase 63 MVA 121 kV/10.5 kV transformer.*

***Streszczenie.** Konstruowanie uzwojeń transformatorów w oparciu o taśmy powlekane nadprzewodnikiem wysokotemperaturowym (taśmy HTS drugiej generacji) jest technologicznie możliwe. Głównym problemem pozostają koszty materiału nawojowego i układu chłodzenia kriogenicznego. W artykule autorzy starają się ocenić wpływ parametrów transformatora na warunki pracy uzwojeń nadprzewodnikowych i tym samym na całkowitą długość taśmy HTS. Obliczenia zostały wykonane dla transformatora trójfazowego 63 MVA 121 kV/10.5 kV. (**Wykorzystanie taśmy nadprzewodnikowe drugiej generacji do uzwajania transformatorów**)*

Keywords: high temperature superconductor, HTS, utility transformer.
Słowa kluczowe: nadprzewodnik wysokotemperaturowy, transformator energetyczny.

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Introduction

Transformers are very numerous in power distribution systems. Electric energy is transformed five to ten times on its way between a power plant and electric appliance [1]. Despite transformer high efficiency, these devices are responsible for approximately 40% of total power losses. Any improvement in transformer efficiency can bring positive economic and ecological results [2].

The idea of superconducting transformer is almost so old as the superconductivity itself. However, the invention and commercialization of high temperature superconductors (HTS, critical temperature $T_c > 25$ K) has opened new possibilities. Problem of cryogenic cooling was tangibly reduced. Liquid nitrogen is safe, easy to obtain and relatively inexpensive. Furthermore, cryocooler efficiency in that temperature range is many times higher comparing to the range required for low temperature superconductors (LTS) [2]. Superconducting transformer may be more efficient, smaller, lighter than its conventional equivalent, safer and environmentally benign. Moreover, it has an intrinsic capability of fault current limitation [1, 2].

Construction of superconducting transformer is not so straightforward as it seems to be. Winding made of superconducting wire transporting AC current especially in external magnetic field generates power losses. Their amount must remain at a very low level comparing to the losses of conventional copper winding. The difference must cover cryogenic cooling expenditures and increased cost of HTS windings. Usage of $YBa_2Cu_3O_7$ (YBCO) coated conductors (second generation HTS tapes, Fig. 1) seems to be the most promising technology these days. The lowest power losses are generated in continuously transposed cable (Roebel cable) – interlaced stack of narrow 2G HTS tapes [1-5].

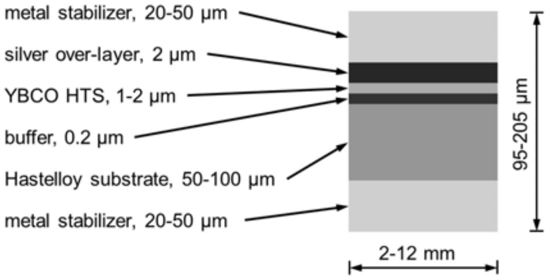

Fig. 1. Cross-section of 2G HTS tape (anisotropic scale)

Superconducting transformer

The concept of superconducting transformer with so-called warm magnetic core (its single phase) is shown in figure 2. Cryogenic cooling penalty factor (cryocooling cost factor) at 77 K is estimated in range of 15-18. This is the reason why it is essential to limit the cooling system load by keeping magnetic core at room temperature. Additionally, cryogenic temperatures do not improve magnetic core performance [1].

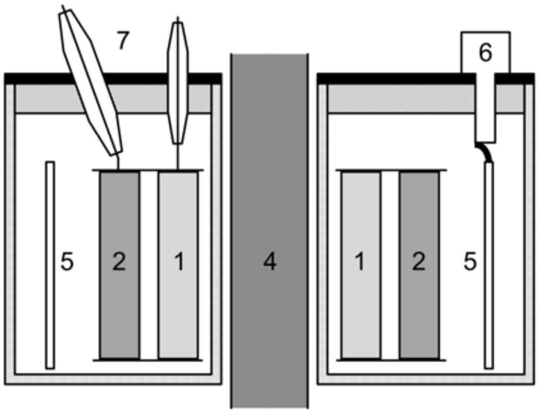

Fig. 2. Conceptual diagram of the cross-section of superconducting transformer (single phase): 1 – low-voltage winding, 2 – high-voltage winding, 3 – liquid nitrogen cryostat, 4 – "warm" magnetic core (core limb), 5 – heat shield/exchanger, 6 – cryocooler head, 7 – current leads (bushings)

Low-voltage (LV) winding 1 and high-voltage (HV) winding 2 of the same transformer phase are placed in the phase cryostat 3. Each of the three toroidal cryostats may be built of a fiber-glass composite with glass microspheres insulation [3]. Cryostats are filled with liquid nitrogen at atmospheric or slightly increased pressure. Heat coming through cryostat walls and current leads 7, heat generated by transport current and eddy-currents induced in all conductors by alternating magnetic field is transferred outside by the heat shield-exchanger 5 connected to the cold-head of the cryocooler 6. Usage of the cryocooler saves liquid nitrogen consumption and permits for versatile temperature control. Lowering temperature of HTS winding to 65 K increases critical current value by the lift factor of 2. It helps to manage long-lasting overloads [5].

HTS transformer design

Superconducting transformer calculation described in this paper is based on the 3-phase 63 MVA 121 kV/10.5 kV conventional transformer design thoroughly described in [6]. General parameters of the transformer project are presented in table 1.

Table 1. Transformer parameters

Parameter	Value
Rated power	63 MVA
Rated voltages	121 kV/10.5 kV
Vector group	Yd11
Frequency	50 Hz
Phase currents (RMS)	301 A/2000 A
Number of winding turns	480/72
Short-circuit voltage	10,1%
Peak magnetic flux density	1,62 T
Magnetic core limb height	1,7 m
Core limb radius	0,41 m
Core weight	38.3 t
Core losses	68,1 kW
Copper weight	7.57 t
Copper losses at rated power	262.6 kW

For the purpose of this analysis, superconducting transformers were designed to have peak magnetic flux in the core, core diameter, core limb height, winding height and the leakage reactance of the conventional unit.

Taking into consideration operational temperature (nitrogen boiling temperature at atmospheric pressure), magnetic field generated by transformer windings (calculated using FEM) and properties of the HTS tape (Fig. 3), it may predicted that the standard winding arrangement (Fig. 4a) is far from optimal for superconducting materials.

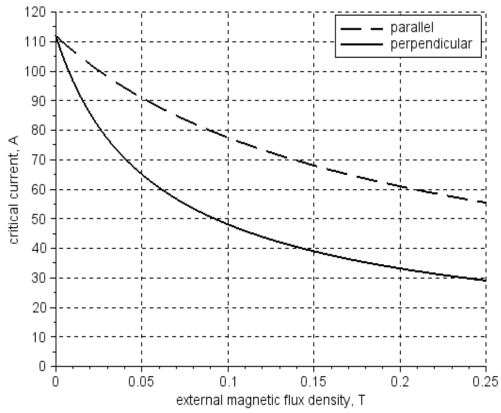

Fig. 3. SuperPower® YBCO 2G tape SCS4050 critical current vs. external magnetic field at 77 K [4]

Advantageous magnetic field distribution and thus improved HTS tape working conditions may be achieved when the low-voltage windings are divided as shown in figure 4b [1]. Analyzing relation between critical current density and magnetic field intensity (Fig. 5 and Fig. 6) it is clear that the LV-HV-LV setup will result in smaller amount of the winding material and in lower AC-losses.

Design results and comparison

HTS tape AC-losses, cryostat losses and current lead losses have been calculated using procedure described in [7]. AC-losses were evaluated on turn-by-turn basis taking into consideration: transport losses (self-field losses), external field losses in HTS and eddy-currents induced in metal layers of the tape.

Total power losses of superconducting transformer with warm magnetic core may be estimated using formula (1):

$$P_t = P_{Fe} + \varepsilon_c \cdot \left(P_{AC} + P_{cr} + P_{cl}\right) \tag{1}$$

where: P_t – total power losses at room temperature, P_{Fe} – magnetic core losses, ε_c – cryogenic cooling penalty factor, P_{AC} – total superconducting tape losses, P_{cr} – cryostat losses, P_{cl} – current lead losses.

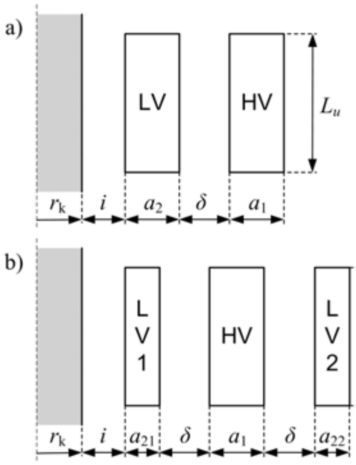

Fig. 4. Arrangements of phase windings: a) standard, b) low voltage winding divided for halves (LV – low voltage winding, HV – high voltage winding)

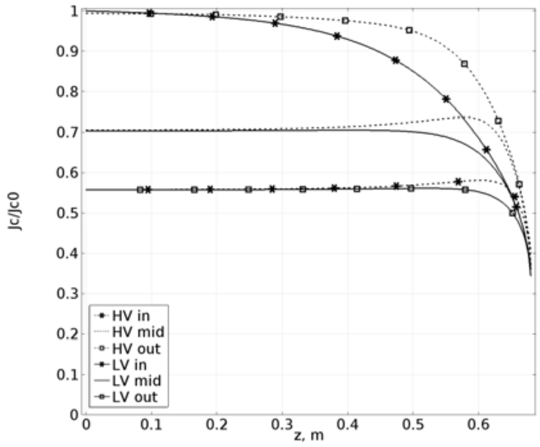

Fig. 5. Relative critical current density distribution along the halves of the transformer windings (J_{c0} – critical current density at self-field, in – cut-line at the inner surface of given winding, mid – cut-line at the winding average radius, out – cut-line at the outer surface)

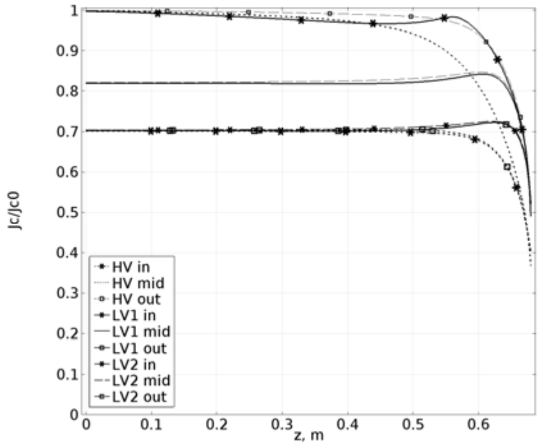

Fig. 6. Relative critical current density distribution along the halves of the transformer windings in LV-HV-LV configuration

The parameters of the superconducting transformers are presented in table 2. The LV-HV-LV winding arrangement requires 134.6 km of SCS4050 tape which is 83% of the tape length needed for standard winding setup. Total power losses at rated workload are equal to 131.8 kW and they are 6.5% smaller comparing to the standard winding organization.

Table 2. Parameters of HTS transformers

Parameter	Value (LV-HV)	Value (LV-HV-LV)
HTS tape dimensions	4 mm x 0.1 mm	
HTS tape critical current (DC, at 77 K, self-field)	112 A	
Nr of parallel tapes in HV winding	17	16
Nr of parallel tapes in LV winding	112	73
Winding height L_u	1,36 m	
Limb-LV winding distance i	50 mm	
HV winding thickness a_1	7,94 mm	6,22 mm
LV winding thickness a_2 (a_{21} a_{22})	7,20 mm	2,06 mm
LV-HV distance δ	112 mm	
Transformer window width	525 mm	749 mm
Core losses	66.9 kW	71,7 kW
HTS tape length for 3 x HV	92.6 km	86.8 km
HTS tape length for 3 x LV	69.6 km	47,8 km
Total area of cryostat walls	29.8 m^2	36.4 m^2
Cryostat losses at 77 K	0.060 kW	0.073 kW
Current lead losses at 77 K	0.52 kW	
HTS tape losses at 77 K	3.12 kW	2.41 kW
Cryocooling penalty factor ε_c	20	
Load losses at room temperature	74.0 kW	60.1 kW

As shown in figure 7, superconducting transformer (LV-HV-LV setup) outperforms conventional unit for workload factor values above 0.25. At the rated power, total power losses in superconducting transformer are equal to 40% of conventional device losses. HTS transformer may be easily redesigned to have lower losses in the full workload range. This can be done at the expense of additional HTS tape length.

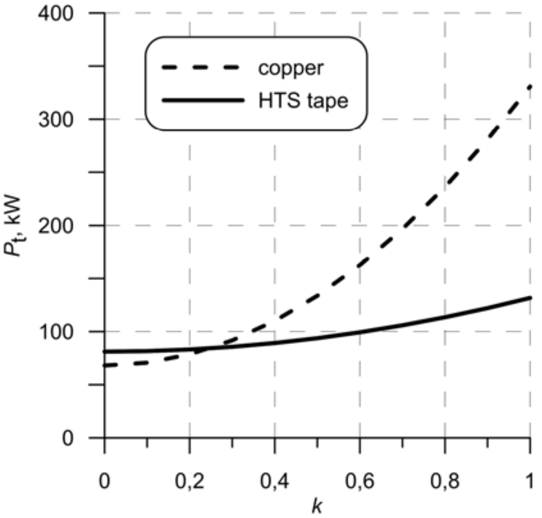

Fig. 7. Comparison of the total power losses in 63 MVA 121 kV/10.5 kV transformers in the function of the workload factor

The loss distribution in 63 MVA HTS transformer (LV-HV-LV setup) is depicted in figure 8. At rated power, magnetic core losses are 54% of total value. Considering cryocooler efficiency, YBCO coated tape AC-losses are 37% of total amount. Remaining 9% are expended in current leads and cryostats.

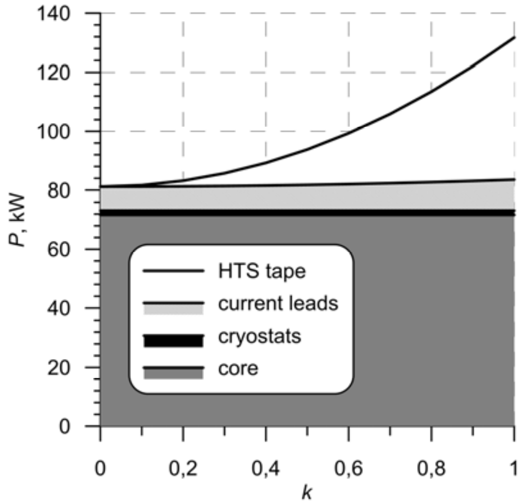

Fig. 8. 63 MVA 121 kV/10.5 kV superconducting transformer losses (LV-HV-LV) vs. workload factor

Conclusion

Conceptual design of the 3-phase 63 MVA 121 kV/10.5 kV HTS 2G transformer with warm magnetic core was completed. The approximate power losses of the conventional transformer and its superconducting counterpart were calculated.

For comparison, copper winding wire for the described construction would cost approximately 120 kUSD. Considering the price of 2G superconducting tape at the projected for year 2013 level of 25 USD/kAm, the raw winding material cost for three-phase 63 MVA transformer may be estimated as 518 kUSD. This must be increased by the price of three cryocoolers in the refrigeration system – 100 kUSD. Disregarding all technological obstacles, assuming that the transformer is able to operate continuously at its rated power, the initial investment could be returned in relatively short period of 3 years.

LITERATURA

[1] Kalsi S. S., *High temperature superconductors to electric power equipment*, IEEE Press, Wiley, 2011

[2] Janowski T., Jaroszyński L., Wojtasiewicz G., Technologiczne I ekonomiczne uwarunkowania budowy transformatorów nadprzewodnikowych, *Prz Elektrotechniczn*, 89, nr 9, pp 40-43, 2013 (in Polish)

[3] Glasson N. D., Staines M. P., Jiang Z., Allpress N. S., Verification testing for a 1 MVA 3-phase demonstration transformer using 2G-HTS Roebel cable, *IEEE T Appl Supercon*, 23, 3, 5500206, 2013

[4] Thakur K. P., Raj A., Brandt E. H., Kvitkovic J., Pamidi S. V., Frequency-dependent critical current and transport AC loss of superconductor strip and Roebel cable, *Supercond Sci Technol* 24, 065024, 2011

[5] Fukushima T., Performance and quality improvements in SuperPower 2G HTS Wires, *23rd International Conference on Magnet Technology 2013* (MT-23), July 15-19, 2013, Boston

[6] Jezierski E., *Transformatory – budowa i projektowanie*, Wyd. 2, WNT, Warszawa, 1963 (in Polish)

[7] Berger A., Cherevatskiy S., Noe M., Leibfried T., Comparison of the efficiency of superconducting and conventional transformers, *J Phys: Conference Series* 234 032004, 2010

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