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doi:10.15199/48.2018.04.19

Temperature increase of the primary winding of a 14 kVA HTS transformer during the flow of the switching current

***Abstract**. When switching on the HTS transformer, through its windings flows an electric current exceeding the value of the critical current of the superconductor. This current deprives the primary winding of its superconducting property, which can result in the winding's thermal damage. The temperature reached by the winding during the flow of the inrush current was calculated. For this purpose, measurements of a 13.8 kVA HTS transformer and derived formulae were used.*

***Streszczenie**. Przy włączaniu transformatora HTS przez jego uzwojenia przewodzony jest prąd elektryczny o wartości przekraczającej wartość prądu krytycznego nadprzewodnika. Prąd ten powoduje utratę stanu nadprzewodzenia uzwojenia pierwotnego, co może skutkować jego termicznym uszkodzeniem. Obliczono temperaturę jaką osiąga uzwojenie w trakcie przepływu prądu włączania. Posłużono się w tym celu pomiarami transformatora HTS o mocy 13,8 kVA i wyprowadzonymi wzorami. (**Wzrost temperatury uzwojenia pierwotnego transformatora HTS o mocy 14 kVA w czasie przepływu prądu włączania**)*

Keywords: superconductivity, transformer, inrush current, temperature.
Słowa kluczowe: nadprzewodnictwo, transformator, prąd włączania, temperatura.

Introduction

Transformer windings can conduct high currents, not only when short-circuited or overloaded, but under certain circumstances even after switching on the transformer to the energy grid. When the no load transformer is switched on, inrush current can reach 20÷40 times the rated current. The disappearing time of the inrush current wave can be up to several thousand periods of the supply voltage.

The main exploitation problem of HTS transformers is the maintenance of the superconducting state of the windings. This is only possible when the point of operation of the superconducting wire P (Fig. 1) is below the critical area determined by absolute critical parameters [1]: critical temperature T_c, critical current I_c, critical magnetic field strength H_c. Exceeding the critical value of any of the parameters T_{cp}, I_{cp}, H_{cp} causes instantaneous loss of superconductivity, as shown in Figure 2 [2].

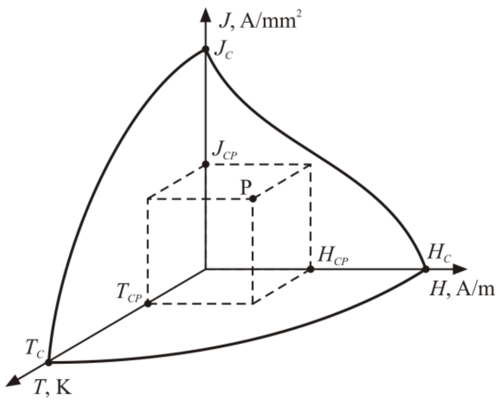

Fig. 1. Critical area of the superconductor

A switching current whose value is higher than the critical I_{cp} for the high voltage winding of the transformer causes the loss of superconductivity in this winding. According to Joule's law, an increase in wire resistance results in an increase in its temperature, which may be higher than the critical T_{cp}. As a result of the temperature increase, the high voltage winding of the HTS transformer may lose its superconducting state for a long time. Long-term significant temperature rise can lead to thermal damage to the superconducting wire.

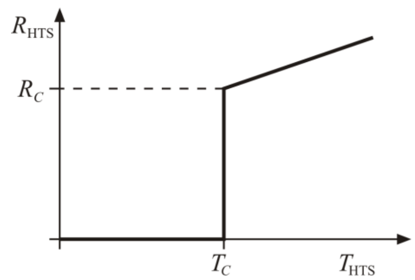

Fig. 2. Simplified characteristics of superconductor transition

HTS Transformer

The tests were performed on a 13.8 kVA transformer (Fig. 3). An overview of the transformer's structure is given in Fig. 4. Table 1 lists the rated characteristics of the transformer.

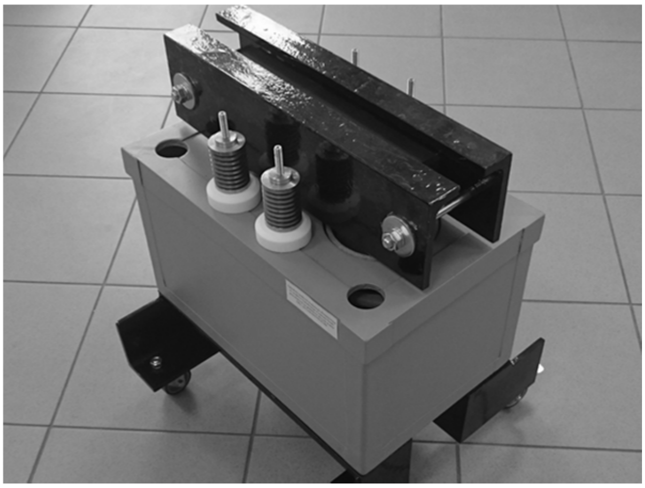

Fig. 3. 14 kVA superconducting transformer

The windings of the transformer were made from superconducting tape by SuperPower Inc. The high voltage winding used tape of the SCS4050-AP type, with a critical current of 87 A at 77K and in its own field. The low voltage windings were made with tape of the SCS12050-AP type with a critical current of 333 A. The winding parameters are given in Table 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%

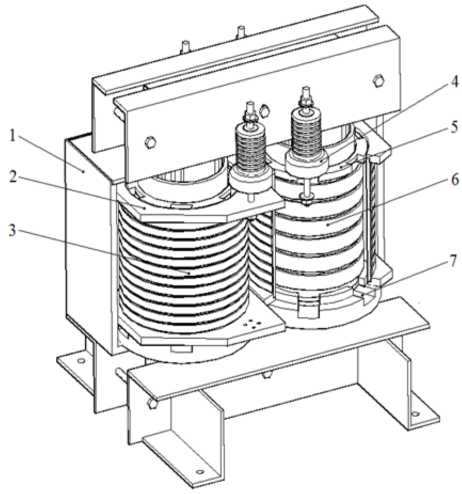

Fig. 4. Outline cross-section of the design: 1 – cryostat, 2 – HV carcass, 3 – HV winding, 4 – bushings current, 5 – LV carcass, 6 – LV winding, 7 – cooling ducts

Table 2. 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

Superconductor wire

High-temperature second generation (2G) superconducting wires are characterised by a complex composite structure that guarantees adequate mechanical and electrical properties and minimises heat loss. The construction of the SCS tape from SuperPower Inc. can be seen in Figure 5, and Table 3 shows its technical parameters [3].

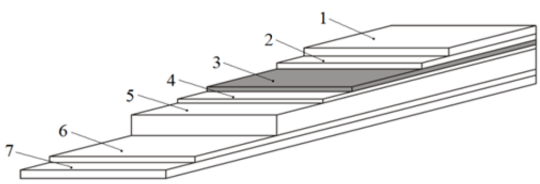

Fig. 5. Construction of superconducting SCS tape by SuperPower Inc.: 1 – copper, 2 – silver, 3 – (Re)BCO, 4 – buffer zone, 5 – Hastelloy, 6 – silver, 7 – copper

The materials used to construct the SCS tape have different heat-specific temperature dependencies (Fig. 6) [4]. The mean value of the specific heat capacity of the tape is calculated from the relation:

$$C(T) = \frac{1}{S}\sum_i S_i C_i(T) \quad (1)$$

where: S – total cross-sectional area of the superconducting tape, S_i – cross-sectional area of the material forming the tape, C_i – specific heat of the material in the tape.

Table 3. Parameters of each layer of superconducting tape

No.	Thickness	Resistivity 20°C	Temperature resistance factor	Heat capacity 20°C
1	20 μm	$1.72 \cdot 10^{-8}$ Ω·m	$3.9 \cdot 10^{-3}$ K^{-1}	390 J/(kg.K)
2	2 μm	$1.59 \cdot 10^{-8}$ Ω·m	$4.1 \cdot 10^{-3}$ K^{-1}	237 J/(kg.K)
3	1 μm	–	–	425 J/(kg.K)
4	1 μm	–	–	–
5	50 μm	$1.26 \cdot 10^{-6}$ Ω·m	$1.3 \cdot 10^{-4}$ K^{-1}	400 J/(kg.K)
6	1.8 μm	$1.59 \cdot 10^{-8}$ Ω·m	$4.1 \cdot 10^{-3}$ K^{-1}	237 J/(kg.K)
7	20 μm	$1.72 \cdot 10^{-8}$ Ω·m	$3.9 \cdot 10^{-3}$ K^{-1}	390 J/(kg.K)

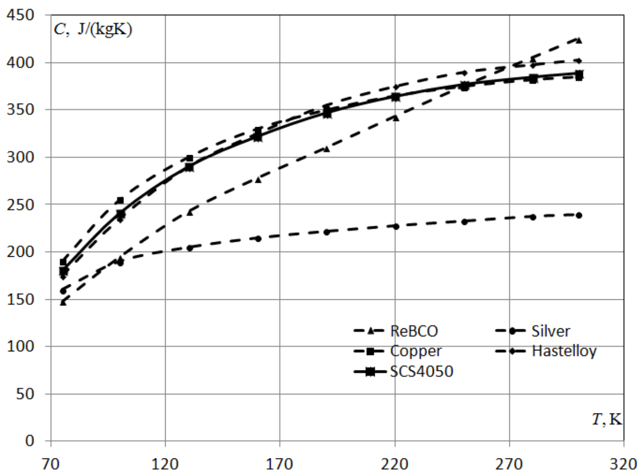

Fig. 6. Specific heat of the materials included in the superconducting tape and the SCS4050-AP tape

Calculation of heat and temperature

The course of the switching current impulse i and the resistance changes of the superconducting tape R are shown in Figure 7. The figure also contains the course of flow in the transformer core φ, and the supply voltage *e*. In the intervals designated as Q_1 and Q_5 unidirectional current impulse does not exist, and in the primary winding of the HTS transformer heat is not generated. Nor is heat produced in compartments Q_2 and Q_4, because the superconductor is in the superconducting state. In such a state the actual resistance of the superconductor is less than 10^{-21} Ω·m, which is a value by 18 orders less than the resistance of copper at room temperature. It can be assumed that in the superconducting state the resistance of the primary winding of the transformer is equal to zero (R=0). The heat in the primary winding is distributed in the Q_3 interval. In this compartment a unidirectional current exceeds the critical value of the superconductor and the winding of the HTS transformer is in the resistive state. The amount of heat that is then emitted in the winding of the HTS transformer is calculated from the dependence:

(2) $$Q_3 = R\int_{-\theta_c/\omega}^{\delta_{cw}/\omega} i^2 dt$$

in which current i in the angle range from θ_c to δ_{cw} is given by the relation [5]:

(3) $$i = -\frac{\sqrt{2}EX}{Z^2}\left(\begin{array}{l}\frac{R}{X}\sin\omega t - \cos\omega t \\ +\left(\frac{R}{X}\sin\theta_c + \cos\theta_c\right)e^{-\frac{R}{X}(\omega t+\theta_c)}\end{array}\right) + I_c e^{-\frac{R}{X}(\omega t+\theta_c)}$$

where: E – effective value of the voltage, R – resistance of the primary winding in the resistive state, X – reactance of the primary winding, Z – impedance of the primary winding in the resistive state, I_c – critical current.

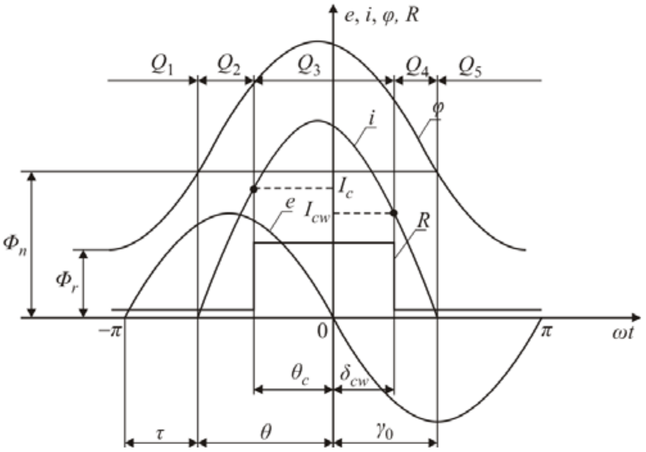

Fig. 7. Intervals in which heat is generated in the windings of the HTS transformer

The primary winding of the transformer exits the superconducting state and goes into the resistive state when the instantaneous value of the switching current impulse i exceeds the critical current value I_c of the superconducting wire. The angle θ_c occurring in equations (2) and (3), at which the primary winding of the transformer goes into the resistive state, is related to the critical current of the superconducting wire and is calculated from the dependence:

(4) $$tg\theta_c = I_c \frac{Z^2}{\sqrt{2}EX}A + B$$

where parameters A and B are:

(5) $$A = \frac{e^{\frac{R}{X}\tau_c}}{\left(\sin\tau_c - \frac{R}{X}\cos\tau_c + \frac{R}{X}e^{\frac{R}{X}\tau_c}\right)\cos(\theta - \tau_c)}$$

(6) $$B = \frac{\frac{R}{X}\sin\tau_c + \cos\tau_c - e^{\frac{R}{X}\tau_c}}{\sin\tau_c - \frac{R}{X}\cos\tau_c + \frac{R}{X}e^{\frac{R}{X}\tau_c}}$$

The angle τ_c in equations (5) and (6) is determined by the equation:

(7) $$\tau_c = \theta - \theta_c$$

in which the angle θ is the angle at which the unidirectional current impulse occurs, calculated from the dependence:

(8) $$\cos\theta = \frac{B_n - B_m - B_r}{B_m}$$

Dependence (8) relates the parameters of the magnetic circuit of the HTS transformer: B_m – maximum induction in the core at nominal operation, B_n – induction of the core saturation, B_r – induction of residual magnetism in the core at the moment of switching on the transformer.

The primary winding of the transformer returns to the superconducting state at the angle δ_{cw}. This angle corresponds to the I_{cw} current (Fig. 7). The I_{cw} current value is usually lower than I_c and depends on the course of thermal phenomena in the superconductor. According to Joule's law, the unidirectional current impulse heats the superconductor when it is in the resistive state. For the superconductor to return to the superconducting state, the instantaneous value of the unidirectional current impulse i must be lower than the superconductor's critical value I_c, and at the same time the temperature of the superconductor must be lower than the critical temperature T_c. If superconductor cooling is inefficient, it will be cooled to a temperature lower than the critical temperature T_c at the instantaneous value of the unidirectional current i lower than the critical value of the superconductor current I_c (Fig. 7).

The temperature increase of the HTS transformer's primary winding during the inrush current impulse is calculated from the dependence:

(9) $$\Delta T = \frac{Q}{mC}$$

where: Q – amount of heat dissipated in the superconducting tape, m – mass of the superconducting tape, C – average volume value of the specific heat of the tape.

Findings

A 13.8 kVA HTS transformer was tested by being switched on, during which time the inrush current flow was recorded. Switching the transformer on was performed under the least favorable conditions when the instantaneous supply voltage was zero. To eliminate the effect of residual magnetism induction values, the switching was realised at zero value. Under these conditions only the first switching current impulse exceeded the critical value of the I_c current of the superconductor.

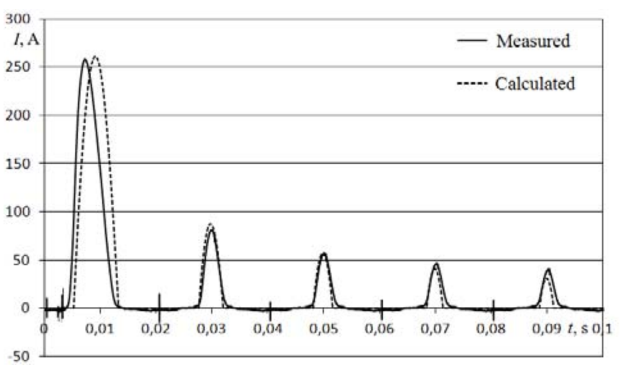

Fig. 8. Inrush current waveform obtained from measurements and calculations

The highest measured value of the first inrush current impulse is 258 A and is 4.3 times greater than the rated current of the transformer and 3 times the critical current I_c. The inrush current waveform obtained from the measurements was compared with the waveform based on dependence (3), the result being good compatibility (Fig. 8). The relative error for the first inrush current impulse was 1.3%.

The maximum heat of 33.1 J is occurs in the primary winding during the first inrush current impulse, when the winding is in the resistive state, in the angle range from θ_c to δ_{cw} (Fig. 9). During the rest of the current impulses the winding does not exit the superconducting state and the amount of heat generated does not exceed 1.68 J for the second impulse and decreases exponentially for successive ones.

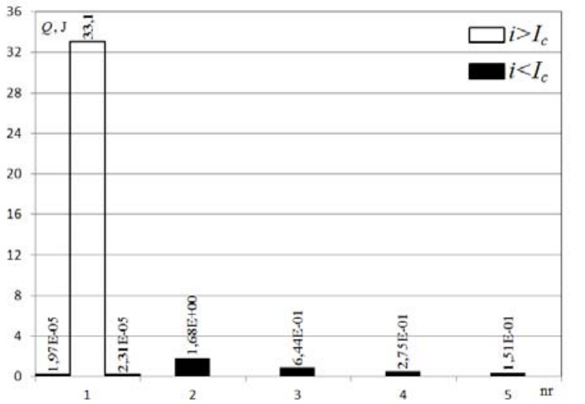

Fig. 9. The amount of heat released on the primary winding resistance with the separated interval where $i>I_c$

The maximum value of the first inrush current impulse I_m significantly depends on the magnitude of the induction of residual magnetism in the core at the moment of switching on the transformer (Fig. 10). Figure 10 shows how the amount of heat released in the transformer's primary winding varies with the value of this induction. Characteristics are derived from the dependences (2) to (9).

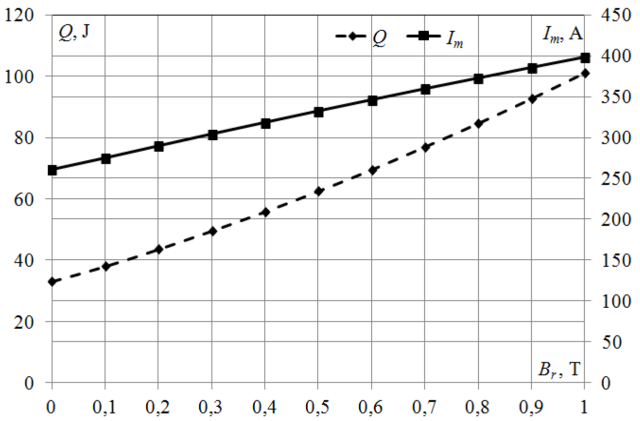

Fig. 10. Change of the maximum value of the first current impulse and the amount of heat released on the resistance of the primary winding in the interval in which $i>I_c$, in the value range of B_r=0÷1 T

The windings of the HTS transformer are cooled with liquid nitrogen and under normal operating conditions they have a temperature of 77 K. The flow of the inrush current causes the temperature of the primary winding to increase. From the point of view of the operation of the superconducting wires it is important that their temperature does not rise above the critical temperature T_c. The result of exceeding this temperature is the loss of the wire's superconducting state and, effectively, its thermal damage. For SCS4050-AP wires, the critical temperature is 92 K. The calculations show that during the inrush current the temperature of the primary windings of the transformer did not exceed the critical temperature. The winding's temperature rise ΔT as a function of the maximum value of the first switching current impulse is shown in Figure 11.

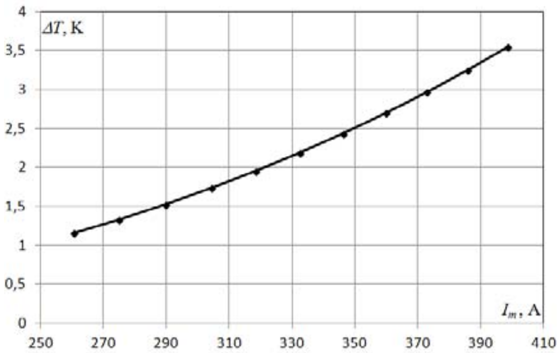

Fig. 11. Increase of primary winding temperature, in the range of B_r=0÷1 T

Conclusions

During several attempts to switching on a 13.8 kVA HTS transformer there was no case of thermal failure of the primary winding. The maximum value that can be reached by the first inrush current impulse is 400 A and 4.6 times the critical current of the SCS4050-AP wire, which is 87 A. In the least favourable conditions, the primary winding of the HTS transformer reaches 80.6 K, i.e. 11.4 K less than the critical temperature of the SCS4050-AP superconducting cable.

The research was conducted in scope of the project "Analysis of inrush current phenomenon and the phenomena related in superconducting transformers." The project was financed with means of National Science Center given with the decision no. DEC-2012/05/D/ST8/02384

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