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Analysis of the current distribution in layers of a second generation superconducting tapes

Streszczenie. *Przewody nadprzewodnikowe drugiej generacji z jakich wykonuje się uzwojenia transformatorów nadprzewodnikowych wykazują dużą podatność na uszkodzenia termiczne. Określenie gęstości prądu w poszczególnych warstwach przewodu HTS 2G pozwala stwierdzić czy uzwojenia transformatora HTS ulegną termicznemu uszkodzeniu w trakcie różnych stanów jego pracy. Przedstawiono i omówiono schemat zastępczy taśmy HTS 2G pozwalający policzyć gęstość prądu w poszczególnych jej warstwach zarówno w stanie nadprzewodzenia jak i rezystywnym warstwy nadprzewodnika. (**Analiza rozpływu prądów w warstwach taśmy nadprzewodnikowej drugiej generacji**)*

***Abstract**. **Abstract**. Second generation superconducting wires from which the windings of superconductor transformers are made are highly susceptible to thermal damage. Determining the density of current in individual layers of the 2G HTS wire allows to find out whether the windings of the HTS transformer will be thermally damaged during various operating conditions. The study presents and discusses a substitute diagram of the 2G HTS tape, allowing to calculate the current density in its individual layers both in the superconducting and resistive state of the superconductor layer.*

Słowa kluczowe: nadprzewodnictwo, taśma nadprzewodnikowa, rozpływ prądów, transformator.
Keywords: superconductivity, superconductor tape, current flow, transformer.

Introduction

Despite good failure statistics, transformers are one of the weak points of the transmission system. That is why a lot of attention is paid to ensuring protection of transformers, which minimises the risk of emergency situations.

The basic operational problem of superconducting transformers (HTS) is the necessity of uninterrupted maintenance of superconducting windings at cryogenic temperature and not allowing losses of the superconducting state in them. The condition in which the HTS windings come out of superconductivity should be treated as an emergency condition of the HTS transformer's operation, which makes switching it on difficult and threatens interrupting the continuity of the windings as a result of their thermal damage.

The substitute diagram of the HTS transformer does not deviate substantially from the conventional transformer scheme (Figure 1).

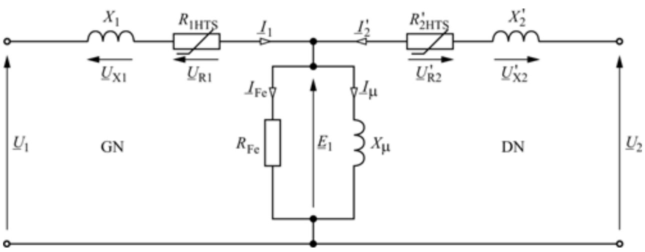

Fig. 1. Substitute diagram of the HTS transformer

Resistances R_{1HTS} and R_{2HTS}, representing power losses in the windings, are non-linear in the function of changes in current intensity, changes in the strength of external magnetic field and temperature changes. The non-linearity of R_{1HTS} and R_{2HTS} resistance is determined by the properties of superconducting winding wires.

Second-generation high-temperature cables (2G HTS), currently used on windings of superconductor transformers, are made in the form of tapes with a layer structure (Fig. 2) [1][2]. They are relatively thin wires, compared to copper winding wires, and the superconductor alone constitutes only 5% of the entire cable's volume. The SCS4050 cable with a critical current of 87 A has a thickness of 0.1 mm and a width of 4 mm. The thickness of the superconductor layer is 1 μm in it. The remaining volume consists of metallic layers. The SCS12050 cable with a critical current of 333 A differs only in its width, which in this case is 12 mm.

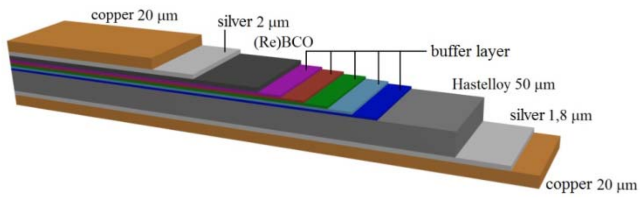

Fig. 2. Structure of the 2G HTS cable from SuperPower Inc. [1]

The general idea of 2G superconductor tape construction along with typical thicknesses of individual layers is shown in Figure 3.

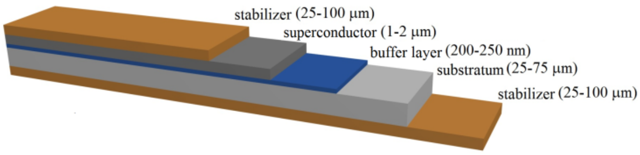

Fig. 3. General idea of 2G HTS cable structure [2]

The high current density in the wire and the small heat exchange surface with the cooling medium make the 2G HTS tapes highly susceptible to thermal damage. Thermal damage of the upper voltage winding of an 13.8 kVA HTS transformer is shown in Figure 4. The winding was made with the 2G HTS tape with the symbol SCS4050-AP.

Fig. 4. Thermal damage of the upper voltage winding of an 13.8 kVA HTS transformer

The damage was caused by multiple switching of the unloaded transformer. The course of the inrush current, which led to the failure of the winding, is shown in Figure 5. The failure was caused by the first pulse, which reached the maximum value of 258 A and exceeded by 171 A the critical value of the SCS4050-AP tape current of 87 A.

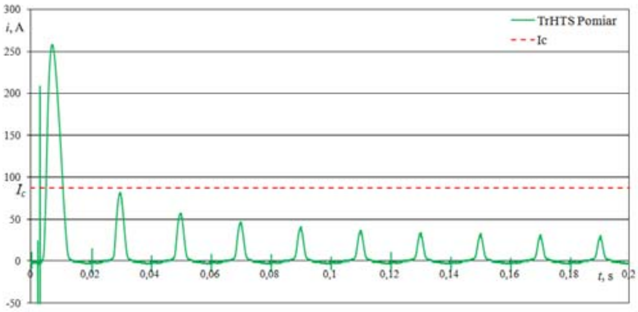

Fig. 5. The inrush current waveform of an 13.8 kVA HTS transformer

The superconducting tape model

The properties of the 2G wire are not the sum or the average of the properties of the individual materials used in its construction. If the electrical parameters of the 2G wire are only considered in the superconducting state, these parameters are determined by the superconductor properties. In the resistive state of the superconductor, the remaining construction materials have a significant influence on the electrical parameters of the conductor.

Using technical methods, it is possible to determine only the substitute resistance of superconducting wire. In this case, the substitute pattern of the superconducting tape is represented by the non-linear resistance R_{st} (Fig. 6).

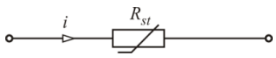

Fig. 6. One-piece substitute diagram of superconducting tape

This approach does not allow to determine the current density in individual layers of the HTS tape, and thereby assess the susceptibility of the HTS transformer winding to thermal damage.

When analysing the tape of SuperPower Inc. (producer symbol SCS4050-AP), whose construction is shown in Figure 2, the substitute diagram of the wire is reduced to six parallel branches representing individual layers (Fig. 7) [3].

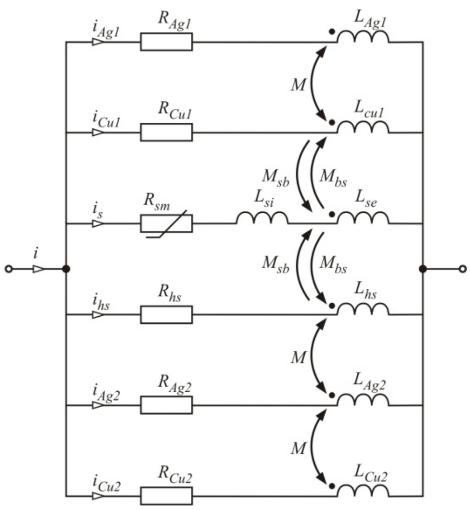

Fig. 7. Substitute scheme of the SCS4050 tape [3]

The parameters of the superconductor layer are described by the non-linear resistance of the R_{sm} superconductor, the inductance representing the hysteresis losses in the L_{si} superconductor and the inductance of the L_{se} superconductor. Superconductor overvoltage layers are described by R_{Ag}, R_{Cu} and R_{hs} own resistances and L_{Ag}, L_{Cu} and L_{hs} own inductances. The M parameters are a measure of the magnetic coupling between the resistive layers. The parameters M_{sb} and M_{bs} are a measure of the magnetic coupling between the superconductor and the resistive layer. M_{bs} determines the ratio of the magnetic flux generated in the superconductor and penetrating the resistive layer to the current flowing in the superconductor. This stream permeates the entire resistive layer, which gives a strong coupling between $M_{bs} \approx L_{se}$ materials. M_{sb} determines the ratio of magnetic flux generated in the resistive layer and penetrating the superconductor to the current flowing in the resistive layer. When the intensity of the magnetic field is lower than the lower critical value for the superconductor, the stream does not penetrate to the superconductor and M_{sb}=0. If the magnetic field strength exceeds the lower critical value, the M_{sb} parameter increases with the approaching field strength to the upper critical value of the superconductor. The 2G HTS tape diagram shown in Figure 7 can be easily modified to suit different needs. In the case of analysing the HTS transformer windings, the diagram in Figure 7 can be simplified to two resistances representing the superconductor layer and the metallic layer (Fig. 8), where L_0 is the inductance of the winding.

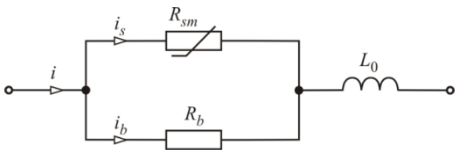

Fig. 8. A simplified diagram of the HTS transformer winding

If the peripheral model of the superconductor wire is presented by the diagram in Figure 8, the conductor resistance of the wire (Figure 6) describes the relationship:

(1) $$R_{st}(B,T,I)=\frac{1}{\dfrac{1}{R_{sm}(B_s,T_s,I_s)}+\dfrac{1}{R_{bn}(T_b)}}$$

where R_{sm} is the superconductor resistance, and R_{bn} is the equivalent resistance of the connected resistive layers expressed by the dependence:

(2) $$R_{bn}(T_b)=\frac{1}{d}\cdot\frac{1}{\sum\dfrac{h_b}{\rho(T_b)}}$$

The non-linear resistance of the R_{sm} superconductor can be described by a set of equations, each of which describes the superconductor parameters in a range of current, temperature and magnetic field strength [4]:

(3) $$R_{sm}(B,T,I)=\begin{cases}\dfrac{E_c}{I_c(B,T)}\cdot\left(\dfrac{I_s}{I_c(B,T)}\right)^{n-1}+R_{s0} & dla\ T<T_c\\ R_{sn}(T)\ \text{dla T} > \text{T}_\text{c}\end{cases}$$

where I_s is the current in the superconductor, R_{s0} is the residual resistor, E_c is the intensity of the electric field at the conduction of the current with the critical intensity I_c. R_{sn} is the superconductor resistance in the normal state. For simplicity, R_{sn}=500 nΩ·m is assumed, and residual resistivity:

(4) $$R_{s0} = \rho_{s0} \frac{l_t}{S_s}$$

where $\rho_{s0}=10^{-14}$ Ωm.

Figure 9 shows the dependence of the resistivity of individual layers of the 2G tape on the temperature [5]. In the low temperature range, the resistivity of metals strongly depends on their purity.

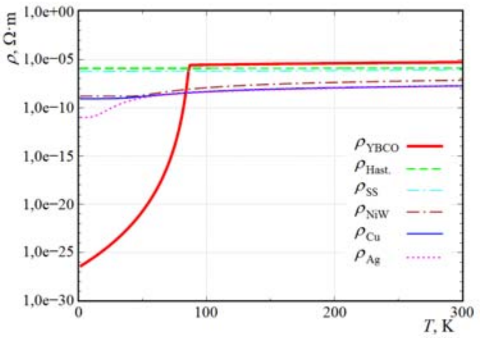

Fig. 9. The dependence of the resistivity of individual layers of the HTS tape on the temperature [5]

The resistivity of the metallic superconductor bypass layers increases with temperature. The variability of copper resistivity in the temperature range from 4 K to 300 K is well described in formula [6]:

(5) $$\rho_{Cu}(T) = \begin{cases} \rho_0 + a \cdot T^2 + b \cdot T^n \;\; dla \;\; T \le 12\,\mathrm{K} \\ \rho_0 + \rho_{ss} \cdot T^5 \cdot \dfrac{J\left(\dfrac{\Theta}{T}\right)}{124{,}14} \;\; dla \;\; T > 12\,\mathrm{K} \end{cases}$$

where:

(6) $$J\left(\frac{\Theta}{T}\right) = \int_0^{\frac{\Theta}{T}} \frac{x^n}{(e^x - 1)\cdot(1 - e^{-x})} dx$$

The parameters present in equations (5) and (6) are: ρ_0=7,6·10^{-12} Ω·m, ρ_{ss}=2,38·10^{-18} Ω·m, a=3·10^{-15} Ω·m/K^2, b=5,4·10^{-18} Ω·m/K^n, n=4,61, Θ=337 K.

The variability of silver resistivity in the temperature range from 4 K to 300 K can be described by the formula:

(7) $$\rho_{Ag}(T) = \frac{\mathrm{C}}{\mathrm{M} \cdot \Theta} \cdot \left(\frac{T}{\Theta}\right)^5 \cdot \int_0^{\frac{\Theta}{T}} \frac{x^5 \cdot e^x}{(e^x - 1)^2} dx$$

where: C=0,0011650123, M=107,868, Θ=220,9 K.

In turn, the relationship describing the resistivity of the Hastelloy alloy has the form:

(8) $$\rho_{Hs}(T) = a \cdot T + b$$

where a=0,1469·10^{-9} Ω·m/K, b=1,229·10^{-6} Ω·m dla T≤12 K, and a=0,2667·10^{-9} Ω·m/K, b=1,234·10^{-6} Ω·m dla T>12 K.

Analysis of current flow

A superconductor transformer with the power of 13.8 kVA and the nominal data given in Table I [7] was analysed. The upper winding (HV) of the transformer was made with superconducting tape SCS4050-AP, and the lower voltage (LV) windings with SCS12050-AP tape. The winding parameters are given in Table II.

Table I. 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%

Table II. 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)	0.0466·10^{-18} Ω /0.0097·10^{-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

The first pulse of the inrush current of the unloaded HTS transformer with the power of 13.8 kVA was taken into account. This is the only impulse that in the case of this transformer exceeds the critical value of the current (87A) of the upper voltage winding. Three current intervals, distinguished during the duration of its impulse, have been analysed (Fig. 10): I – instantaneous current does not exceed the critical value for the upper voltage winding and it is in the superconducting state, II – the current has exceeded the critical value and the winding has changed to resistive state, III – the current is lower than the critical value and the winding is superconducting.

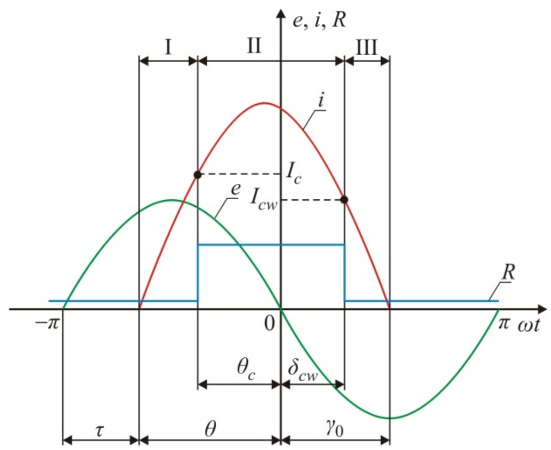

Fig. 10. The course of the inrush current impulse and changes in resistance of the HTS transformer winding during its duration and the power supply voltage; R – resistance of the superconductor transformer winding, e – supply voltage, i – one-way current pulse of the superconductor transformer, I_c – critical current of the transformer winding, I_{cw} – current at which the winding returns to the superconducting state

In compartments I and III, the transformer winding is superconducting, its resistance is zero and almost all of the current is conducted through the superconductor layer in the SCS4050-AP tape. The situation changes after the superconductor has passed the resistive state when the impulse of inrush current on the critical value is exceeded, i.e. for the third compartment.

The tests show that the average temperature of the SCS4050-AP tape during the first impulse of the 13.8 kVA HTS inrush current does not increase by more than 3.6 K. During the impulse of the inrush current, with the maximum possible peak value for this transformer of 398 A, the SCS4050-AP tape heats up to 80.6 K (Fig. 11) [8] and thus does not reach the critical temperature, which is 92 K for this tape. It is difficult to determine the temperature of the individual construction layers of the tape, because in addition to the current density in a given layer, its temperature is affected by changes in resistivity, specific heat, thermal conductivity (which parameters change with a change in the temperature of the material) and cooling efficiency of liquid nitrogen.

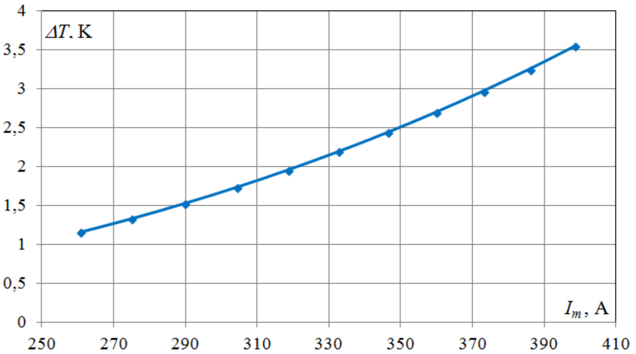

Fig. 11. Increase of the temperature of the primary winding of the HTS transformer for various peaks of the inrush current impulse [8]

It is a great difficulty to determine the mutual inductances between the superconductor tape layers in its equivalent scheme shown in Figure 7. In the calculations these couplings are omitted. The inductance of individual layers and the inductance representing the hysteresis losses in the superconductor were also omitted.

The calculations show that in the resistive state of the SCS4050-AP tape, in the range of its temperature changes from 77 K to 80.6 K, there are relatively small changes in the distribution of instant current density in its individual structural layers (Table III). The biggest changes occur for the superconductor and they amount to 5.5 A/mm^2. It results from large changes in the resistivity of the superconductor in this temperature range (Fig. 9). Metallic layers in this temperature range have relatively small changes in resistivity, hence small changes in the current density.

During the inrush current of the HTS transformer with the power of 13.8 kVA, after passing the SCS4050-AP tape to the resistive state, the highest instantaneous current density is recorded in the silver layer and amounts to 1100.2 A/mm^2 (Table III). A slightly lower value of 990.1 A/mm^2 is recorded for the copper layer. For the Hastelloy layer, the instantaneous current density is only 13 A/mm^2. A slightly higher current density occurs in the superconductor and is 45.5 A/mm^2.

Table III. The maximum current density in the layers for the resistive state of the superconductor tape

T	Cu	Ag	Hast. C-276	(RE)BCO
77 K	990 A/mm^2	1100 A/mm^2	13 A/mm^2	44 A/mm^2
80,6 K	990,1 A/mm^2	1100,2 A/mm^2	13 A/mm^2	45,5 A/mm^2

Summary

Despite the high current densities that occur in the copper and silver layers of the SCS4050-AP tape, after its transition to a resistive state, during the inrush current of the HTS transformer with the power of 13.8 kVA, there was no case of thermal damage to the upper voltage winding. The SCS4050-AP tape superconductivity lasts for 5.6 ms, and the instantaneous current densities given in Table III are recorded for the peak value of the first impulse of the inrush current. With such a short duration of the resistive state and at such instantaneous current densities in individual SCS4050-AP tape layers, the cooling liquid nitrogen efficiency of the 13.8 kVA HTS transformer windings is so large that the average belt temperature increase is only 3.6 K. The thermal damage of the upper voltage winding shown in Figure 4 took place after repeated attempts to turn on the unloaded transformer. It should be assumed that while even the largest inrush current possible for the HTS transformer does not lead to thermal damage to the SCS4050-AP tape, yet it causes gradual degradation of the tape structure, which results in its damage after a certain number of transformer inclusions.

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