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Increase in losses in a superconducting transformer due to inrush current

Streszczenie. *W pewnych okolicznościach, włączeniu nieobciążonego transformatora nadprzewodnikowego do sieci towarzyszyć może prąd włączania o dużej wartości. Na skutek nasycenia rdzenia, pole magnetyczne w kolumnie wielokrotnie przekracza wartość obliczeniową. W efekcie może mieć miejsce przekroczenie krytycznych wartości prądu oraz natężenia pola materiału nadprzewodnikowego, uzwojenia transformatora przechodzą ze stanu nadprzewodzenia do stanu rezystywnego. Wzrost strat przekłada się na wzrost temperatury nadprzewodnika, mogący prowadzić do termicznego uszkodzenia uzwojeń. W pracy poddano analizie wzrost strat w uzwojeniu transformatora HTS na skutek przepływu prądu włączania.* ***Wzrost strat w transformatorze nadprzewodnikowym w skutek przepływu prądu włączania.***

Abstract*. In some cases after the superconducting transformer is switched into the energetic network, core saturation occurs. Magnetic field is many times greater than the calculated field. The outer magnetic field causes increase in losses in superconducting transformer's windings. The effect is getting the windings from superconducting to resistive state. Increase in windings temperature in the resistive state can lead to irreversible superconductor degradation.*

Słowa kluczowe: prąd włączania, transformator, nadprzewodnik, straty.
Keywords: inrush current, transfromers, superconductor, losses.

Introduction

The most useful feature of superconductors, with different practical applications in mind, is their ability to conduct great currents with minimal energetic losses. In a no load superconductive transformer (HTS) total losses are 50% and in full load 10% of losses a transformer with copper windings.

The basic problem with exploitation of HTS transformers is maintaining their windings in superconductive state. Crossing any critical value of superconductor like critical temperature T_c, critical magnetic field rate H_c and critical current density J_c causes getting the superconductor from superconducting to resistive state. The transition is accompanied by increase in Jolue losses. Increase in windings temperature causes vaporization of liquid nitrogen and in extreme cases destruction of the structure of the superconductor.

The loss in superconductive state can happen while switching on the transformer [1]. It is when a transient state occurs in the electric circuit coupled to magnetic field. The inrush current flowing through HTS transformer's windings in the transient state causes increase in superconductor losses. When the losses are too great, may prevent the switching on of the transformer and even cause a winding thermal damage.

Inrush current

A transformer's inrush current is a sum of two constituents: transformer's no-load current and unidirectional current. The unidirectional constituent appears when the transformer's core is saturated. The unidirectional current's decay time and its magnitude depend on transformer's electric and magnetic parameters, the supply network's impedance and initial conditions while switching the transformer on, that is instantaneous value of the voltage and the core magnetization. In some given circumstances the unidirectional current can have a value 40 times higher than the transformer's rated current. Time of inrush current decay can be up to more than several thousands periods of supply voltage. With such huge unidirectional current values the constituent representing the no-load current can be omitted in further calculations.

The unidirectional current momentary value can be derived from the following formula [2]:

$$i = -\frac{\sqrt{2}EX}{Z^2}\left(\frac{R}{X}\sin\omega t - \cos\omega t\right) - \frac{\sqrt{2}EX}{Z^2}\left(\frac{R}{X}\sin\theta + \cos\theta\right)e^{-\frac{R}{X}(\omega t+\theta)} \quad (1)$$

where: E – the effective voltage value, ω – pulsation, t – time, R – resistance of the primary transformer's winding, X – the winding's reactance, Z – the winding's impedance. The angle θ present in the formula (1) is derived from the relation [2]:

$$\cos\theta = \frac{B_n - B_m - B_o}{B_m} \quad (2)$$

where B_n – the induction of transformer's core saturation, B_m – the rated induction, B_o – the induction of residual magnetism.

Basing on equation (1) the unidirectional current effective value can be calculated:

$$I = \left(\frac{\omega}{2\pi}\int_{-\theta/\omega}^{\delta/\omega} i^2 dt\right)^{\frac{1}{2}} = \frac{E_m}{X}\left(\frac{H}{2\pi}\right)^{\frac{1}{2}} \quad (3)$$

where H parameter is derived from the formula:

$$H = \frac{X^2}{4Z^2}\left(2(\delta+\theta) - \sin 2\delta - \sin 2\theta\right) - \frac{X^3}{4RZ^2}\left(\cos 2\delta - \cos 2\theta\right) \quad (4)$$

The δ angle in formula (4) is derived from the equation:

$$tg\delta = \frac{e^{\frac{R}{X}\gamma} - \frac{R}{X}\sin\gamma - \cos\gamma}{\frac{R}{X}e^{\frac{R}{X}\gamma} + \sin\gamma - \frac{R}{X}\cos\gamma} \quad (5)$$

where γ is the angle representing the unidirectional current lasting time:

$$\gamma = \theta + \delta \quad (6)$$

Losses in HTS transformer

Power losses in a HTS transformer consist of three components: superconductor losses, iron core losses, cryostat losses and current lead losses. Graph of losses in 3-phase 63 MVA HTS transformer is shown in Figure 1 [3]. Out of the mentioned only losses in windings and current lead losses are determined by current flow.

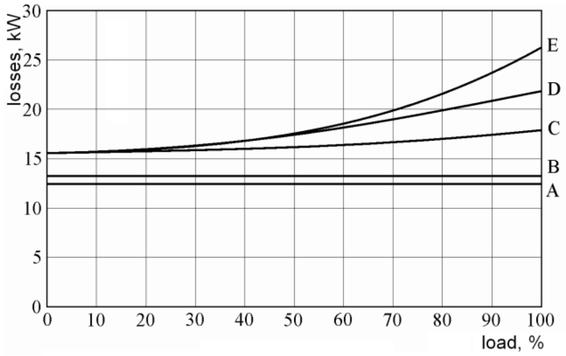


Fig. 1. Losses in 63 MVA HTS transformer [3]: A - iron core losses, B - cryostat losses, C - current lead losses, D - losses in winding caused by external field, E - losses in winding caused by self field.

Losses in windings

Losses in transformer's superconductive windings are caused by changing magnetic field. Given the source of the field we can distinguish between losses caused by external magnetic field, that is hysteretic and eddy current, and losses caused by self field.

The source of losses caused by self field is the current flowing through superconductive windings. The losses, calculated for a unit of superconductive tape length, are derived from Norris formula[4]:

$$P_p = \frac{\mu_0 \cdot f \cdot I_c}{\pi} \left(\begin{array}{l} \left(1 - \frac{I_t}{I_c}\right) \cdot \ln\left(1 - \frac{I_t}{I_c}\right) + \\ \left(1 + \frac{I_t}{I_c}\right) \cdot \left(1 + \frac{I_t}{I_c}\right) - \left(\frac{I_t}{I_c}\right)^2 \end{array} \right) \tag{7}$$

where I_t – transport current, I_c – critical current, f – frequency, μ_0 – vacuum magnetic permeability.

The source of hysteresis and eddy current losses is the leakage flux of the transformer windings. Due to the strong anisotropy of the superconductor, the component of the external magnetic field perpendicular to the superconducting tape (Fig. 2) causes greater losses than the parallel component.

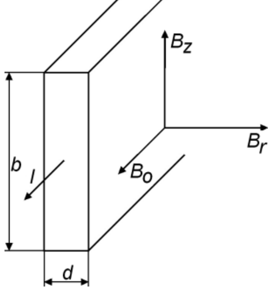


Fig.2. The superconductor's measurements and magnetic field vectors orientation

The losses per unit length of the tape, due magnetic field applied perpendicular to the face of a superconducting strip, can be expressed as [5][6]:

$$P_r = \frac{K f \pi b^2}{\mu_0} B_r B_c \left(\frac{2B_c}{B_r} \ln\left(\cosh\left(\frac{B_r}{B_c}\right)\right) - \tanh\left(\frac{B_r}{B_c}\right)\right) \tag{8}$$

where B_r – magnetic field perpendicular constituent, B_c – critical field of superconductor's penetration, f – frequency, μ_0 – vacuum magnetic permeability, K – tape's shape geometrical factor, b – superconductive tape's width.

The losses caused by the magnetic field parallel to the superconductor can be expressed from the formula [5] [6]:

$$P_z = \begin{cases} \frac{2 fACB_z^3}{3\mu_0 B_p}, & B_z \le B_p \\ \frac{2 fACB_p}{3\mu_0}\left(3B_z - 2B_p\right), & B_z > B_p \end{cases} \tag{9}$$

where B_z – field parallel constituent, B_p – the field which causes full superconductor's penetration, f - frequency, μ_0 – vacuum magnetic permeability, A – tape cross-section field, C – relation between superconductor layer's cross-section field and tape cross-section field, J_c – critical current density, d – superconductor's thickness.

Given necessity to ensure stable functioning, to minimize thermal losses and to ensure the right mechanical endurance, superconductive winding cables have composite structure. In Fig. 3 the structure of tape SCS4050 with critical current I_c=115 A is presented, and in Table 1 details of every layer materials are enclosed. Hastelloy, copper and silver are used as stabilizers. The buffer layer prevents chemical reactions between metal bed and superconductor.

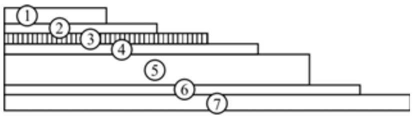


Fig. 3. Structure of SuperPower SCS4050 tape

Table 1. Structure of SuperPower SCS4050 tape

Layer number	Thickness	Material
1	20 μm	Copper
2	2 μm	Silver
3	1 μm	(RE)BCO
4	1 μm	Buffer layer
5	50 μm	Hastelloy C-276
6	1,8 μm	Silver
7	20 μm	Copper

The flux, caused by the current flowing in the superconductor, penetrates the entire surface of the stabilizer which results in a strong coupling between materials [7]. As a result, the entire volume of the resistive layers are induced eddy currents. Eddy current losses can be derived from the equation [8]:

$$P_w = \frac{a}{\rho}\left(\frac{f}{100}\right)^2 B^2 \tag{10}$$

where B – outer magnetic field, f – frequency, a – resistive layer thickness, ρ – resistance of the resistive layer.

In superconductive tapes current of certain density, relevant on superconductor's functioning state, flows through the resistive layers causing Joule's losses:

$$P_a = \frac{\rho}{S} I_a^2 \tag{11}$$

where ρ – resistance of the resistive layer, S – the resistive layer cross-section field, I_a – the current flowing through the resistive layer.

In the windings superconductive state, given small current density in resistive layers, the losses can be omitted. The losses increase considerably in resistive state of the superconductive tape. At room temperature, electrical conductivity of high temperature superconductors is comparable to conductivity of some unstructured metallic alloys. So with increase in temperature of superconductor, function of stabilizing layers in current conducting increases.

Losses in current lead

For current lead working between 40 to 100 K solid superconductive materials are used or superconductive tapes. High temperature current lead working at between 100 to 300 K are made of copper profiles.

Joule's losses generated by the current lead are derived from the formula:

$$P_p = \frac{\rho_p}{S_p} I^2 \tag{12}$$

where ρ_p – current lead resistance, S_p – current lead cross-section, I_a – current flowing through the current lead.

Inrush current flow consequences

Analyzing losses in superconducting transformer caused by inrush current, two ranges of unidirectional current value must be considered: (1) the current value is between 0 and the superconductor's critical current value; (2) the current exceeds the critical value. The value and decay time of inrush current depends on the electrical and magnetic parameters of the transformer, impedance of power supply and the initial conditions, i.e. voltage and residual flux. In Figure 4 the inrush current flow in a one-phase HTS transformer of 8.5 kVA was presented [9]. This course was obtained from measurements.

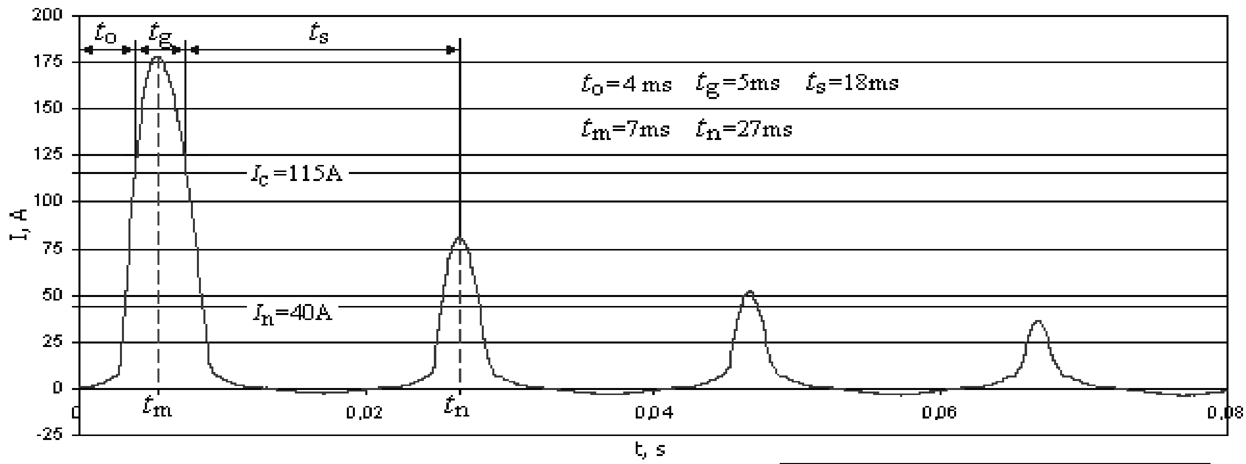
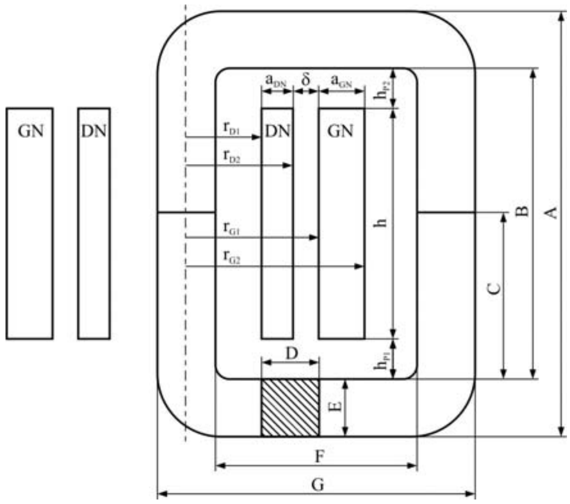


Fig. 4. Inrush current flow in time, in an superconducting transformer

The geometry of the examined transformers is shown in Figure 1. The nominal data of the transformer are shown in Table 2. For construction of magnetic circuit of a HTS transformer a wound and cut core RZC-70/230-70 the power 8.5 kVA was used, constructed of sheet metal PN ET52-27, containing 3% grain-oriented silicon and sheet thickness of 27 mm. The saturation flux density B_s=1.7 T at H=10 A/cm and core losses P=0.8 W/kg at B=1 T. The hysteresis loop of the core shown in Figure 6. Primary and secondary windings were constructed with superconducting tape Super Power SCS4050 of critical current 115 A in temperature 77K and self field.



r_{D1} = 65.6	r_{D2} = 65.9	r_{G1} = 66.0	r_{G2} = 66.7	δ = 0.1
a_{DN} = 0.3	a_{GN} = 0.7	h = 140	h_{P1} = 45	h_{P2} = 45
A = 370	B = 230	C = 115	D = 70	E = 70
F = 70	G = 210			

Fig. 5. Transformer dimensions

Table 2. Nominal data of the transformers

Power	10 kVA
Frequency	50 Hz
Voltage HV/LV	230 V/115 V
Current HV/LV	44 A/88 A
Magnetic induction	1.6 T
No load current	3.1 A
% impedance	0.9%

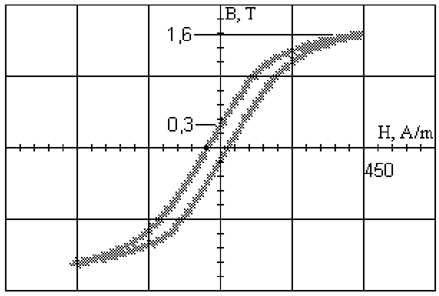


Fig. 6. Hysteresis of the RZC-70/230-70 core

For the time range t_0 (Fig. 4) the inrush current value is lower than the critical current value, the superconductor is in superconducting state. This is the range of current values expected in typical transformer's exploitation. So the losses in the transformer's windings and in the current lead are in the range of normal exploitation losses. Losses caused by self field increase according to Norris formula (7) and the eddy current losses according to the equation (10). At the moment when the inrush current exceeds the critical current value of the superconductor, that is in the t_g time range in Fig. 1, the transformer's windings goes into the resistive state. A jump in winding's resistance occurs and the unidirectional inrush current constituent is described by the equation (1). In Table 3 a 8.5 kVA transformer's winding resistance value at different working stages was given:

Table 3. Superconducting transformer's primary winding resistance

Superconductive state 77K	$0.055 \cdot 10^{-18}\ \Omega$
Resistive state 77K	$0.594\ \Omega$
Resistive state 293K	$6.36\ \Omega$

Joule's losses described by the (11) equation appear in transformer's winding, and at the same time, according to the equation (12) losses in current lead increase. Due to increase in superconductive material's resistance the current distribution in different layers of superconductive tape changes. Which translates into a significant increase in losses in the resistive layers of superconducting tape. According to calculations [9], in tape SCS4050 resistive state, at 77K, 89% of the current flows through copper, 9.4% through silver and 1.5% through Hastelloy layer. Increase in temperature causes change in each layer's material resistance. In effect, there is the change in current distribution. At 293K the ratio is respectively 88.7%, 9.5% and 1.5%. An excessive increase in Joule's losses can cause overheating of windings. In consequence there might be an increase in losses of liquid nitrogen and even destruction in superconductive tape's structure.

The cause of unidirectional current appearing is transformer's core saturation. In the least favourable case the field strength reaches the maximum described by the equation [10]:

(14)
$$H_{\mathrm{M}} = \frac{B_{\mathrm{M}} - B_{\mathrm{n}}}{\mu_0 \dfrac{A}{A_{\mathrm{k}}}}$$

where B_m – rated induction, B_0 – residual induction, A_k – iron cross-section, A – winding cross-section. This value is many times higher than calculated intensity of the magnetic field. The impact of induction on the increase of hysteresis loss depending on the ratio of the parallel component to the perpendicular component of the field.

Conclusions

Great values of magnetic field, occurring during switching on HTS transformer, lead to increase in losses in superconducting windings. Magnitude of the losses depends on the windings structure and positioning of the superconducting tapes against the magnetic field force line. Crossing one of superconductor's critical value, e.g. critical current density, critical temperature, critical field intensity causes getting the transformer's windings from superconducting to resistive state. Increase in losses in the superconducting tape might lead to irreversible degradation of the superconductor. In resistive layers of windings there are induced eddy currents and heating of thin layers of copper and silver occurs. So inrush current can cause problems with switching a superconducting transformer on and in extreme cases can lead to damage in windings.

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