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Impact of the voltage phase angle at the time of switching on the HTS transformer on the loss of winding superconductivity

Streszczenie. *Utratę stanu nadprzewodzenia uzwojeń transformatora nadprzewodnikowego traktuje się jako stan awaryjny. Stan taki może mieć miejsce już w chwili włączania transformatora w skutek wystąpienia prądu włączania. Wartość tego prądu może wielokrotnie przekraczać wartość prądu krytycznego uzwojeń nadprzewodnikowych i zależy od wielu czynników. W przedstawionej analizie wzięto pod uwagę wpływ kata fazowego napięcia w chwili włączenia transformatora na utratę stanu nadprzewodzenia uzwojeń jednofazowego transformatora HTS o mocy 13.8 kVA. (**Wpływ kąta fazowego napięcia w chwili włączenia transformatora HTS na utratę stanu nadprzewodzenia uzwojeń**).*

Abstract*. The superconducting superconducting state of the superconducting transformer windings shall be treated as an emergency state. Such a state may occur already at the moment of switching on the transformer due to the inrush current. The value of this current can be many times higher than the critical current of superconducting windings and depends on many factors. In the presented analysis, the influence of the phase execution of voltage at the moment of switching on the transformer on the loss of superconductivity of the one-phase HTS transformer with the power of 13.8 kVA was taken into account.*

Słowa kluczowe: prąd włączania, transformator nadprzewodnikowy, nadprzewodnictwo.
Keywords: inrusch current, superconducting transformer, superconductivity.

Introduction

The loss of superconducting state of superconducting windings of a superconducting transformer (HTS) at the moment of its switching on is an undesirable phenomenon. This phenomenon makes it difficult to connect the transformer to the power network, creating the risk of thermal damage and interruption of the windings. When the HTS transformer is switched on, its windings may lose their superconductive state as a result of the inrush current flow. The value of this can be many times higher than the rated current of the transformer and thus the critical value of the current of the superconducting windings. The value of the inrush current will depend on many factors, the most important of which are: the phase angle of the transformer supply voltage at the moment of its switching on, the value of residual magnetism flux in the transformer core at the moment of its switching on, the value of the resistance of the transformer windings. In this paper the influence of the phase angle of power supply voltage at the moment of switching on the HTS transformer on the loss of superconducting state of its windings has been analyzed.

Transfromator HTS

The design of the HTS transformer does not fundamentally differ from the design of an ordinary transformer [1]. The existing differences are dictated by the application of superconducting conductors to windings, whose parameters and properties differ significantly from conventional copper or aluminium winding conductors. The most important feature of superconducting wires is zero resistance (superconducting state) in cryogenic temperature. This resistance may rapidly increase (loss of superconducting state and transition to resistive state) as a result of exceeding any critical value of superconducting wire [2]: critical temperature T_c, critical current I_c, critical intensity of magnetic field H_c. The loss of superconducting state is accompanied by a rapid temperature rise of the superconducting wire according to Joule-Lenz's law. The temperature of a superconducting wire in a resistive state can reach significant values due to the high current densities typical of this type of wire. While the loss of superconductivity of HTS transformer windings occurs relatively easily, the return to this state is difficult. In order for the superconducting winding to return to the superconducting state at the same time all parameters must have values lower than the critical ones.

Inrush current

The inrush current of conventional transformers is a relatively well recognized phenomenon [3]. In the case of HTS transformers, there is little information about this phenomenon. Experimentally, it was found that the inrush current of HTS transformers reaches higher values and longer wavelength decay times in comparison to conventional transformers. The differences in resistance of windings of both types of transformers play an important role here.

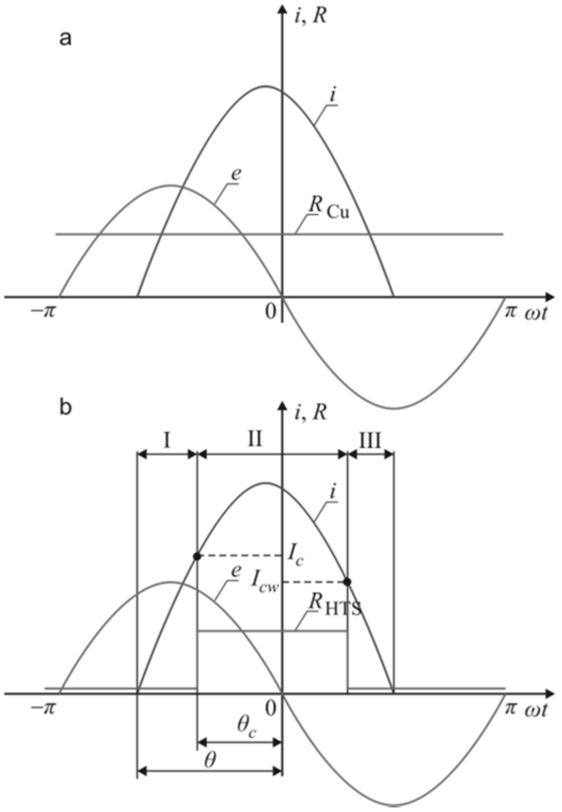

Fig. 1. Resistance of windings during the inrush current pulse: a) conventional transformer, b) HTS transformer, I, III - superconducting state of windings, II - resisting state of windings

Resistance of conventional transformer windings is a constant value for the whole duration of the inrush current (if one omits the resistance changes related to the heating of windings due to the current flow). The resistance of the HTS transformer windings depends on their state (superconductivity or resistive) and may change many times during the inrush current.

The proper operating state of the HTS transformer windings is the superconducting state. In the superconducting state (interval I and III in Fig. 1b) the actual resistance of the superconductor is less than 10^{-21} $\Omega\cdot$m, which is 18 rows less than the resistance of copper at room temperature. It can be assumed that in the superconducting state the resistance of HTS transformer windings is equal to zero (R_{HTS}=0).

The transformer windings go to the resistive state when the momentary switching current exceeds the critical current I_c of the HTS cable (interval II in Fig. 1b). The resistance of the windings then increases rapidly to the value typical for a given type of HTS cable.

Transformer windings return to the superconducting state usually for a momentary value of inrush current I_{cw} lower to the critical value I_c ($I_{cw} \leq I_c$). The temperature of the T_{HTC} windings plays an important role here, which must be lower to the critical value of T_c ($T_{HTC}<T_c$) in order for the HTS windings of the transformer to return to the superconducting state. The speed at which the windings will be cooled down to a temperature lower than critical depends on the I_{cw} inrush current value, at which the superconductivity will be restored.

The inrush current of the transformer has two components [4][5]: (1) determined as being essentially the idle current magnetising the core under the conditions of the transformer operation, (2) the disturbance resulting from the existence of a unidirectional current under transitional conditions. From the point of view of further analysis, the current disturbing component is important. The determined component will be omitted from the considerations.

The unidirectional inrush current appears at the moment of saturation of the transformer core and disappears after the normal state of its operation is restored. The pulse of the unidirectional current appears for the angle given by equation (1):

$$\cos\theta = \frac{B_n - B_m - B_r}{B_m} \qquad (1)$$

where: B_n - saturation induction of the core, B_m - nominal maximum induction, B_r - residual magnetism induction in the core at the moment of switching on the transformer.

Knowing the value of the θ angle, the formula for a unidirectional pulse of the switching current can be derived. When the transformer core is saturated, its substitution scheme in the idle state is reduced to a serial connection of the resistance of the primary winding R_{HTS1} and the inductance of this winding L_{HTS1}, which writes equation (2):

$$-E_m sin(\omega t + \alpha) = R_{HTS1} i + L_{HTS1} \frac{di}{dt} \qquad (2)$$

where: E_m - maximum voltage value, α - phase shift angle.

The unidirectional current pulse appears for $\omega t = -\theta$ and in the initial conditions is equal to zero i=0. After the integration of equation 2 the equation for unidirectional current in interval I is obtained (Fig. 1b) (3):

$$i = -\frac{E_m X_{HTS1}}{Z_{HTS1}^2}\left[\frac{R_{HTS1}}{X_{HTS1}} sin(\omega t + \alpha) - cos(\omega t + \alpha) - \left(\frac{R_{HTS1}}{X_{HTS1}} sin(\alpha - \theta) - cos(\alpha - \theta)\right) e^{-\frac{R_{HTS1}}{X_{HTS1}}(\omega t + \theta)}\right] \qquad (3)$$

where: X_{HTS1} - circuit reactance, Z_{HTS1} - circuit impedance.

Taking the zero value of the resistance of the primary winding of the HTS transformer in the superconducting state R_{HTS1}=0, equation (3) is simplified to the form (4):

$$i = -\frac{E_m}{X_{HTS1}}[cos(\alpha - \theta) - cos(\omega t + \alpha)] \qquad (4)$$

Formula (3) apart from the resistance of superconducting wires allows to take into account the resistance of all structural elements of HTS transformer windings, i.e. soldered connections, connectors, copper structural elements, current culverts. Then, instead of the resistance R_{HTS1}, insert the sum of all these resistances.

From equation (3) it follows that the course of the unidirectional current pulse significantly depends on the α phase angle of voltage at the moment of switching on the transformer. If the transformer is switched on when the voltage reaches the maximum value, i.e. for the phase angle of voltage $\alpha=-\pi/2$, then the unidirectional current will not occur and the magnetizing no-load current will flow immediately. It results from the fact that the flux in the core is shifted in relation to the voltage by the angle $\pi/2$, so in the discussed situation at the moment of switching on the transformer the flux goes through zero. The least favourable conditions for switching on the transformer are when the voltage goes through zero, then the flux in the core reaches the maximum value and thus the unidirectional current reaches the highest value.

The phase angle of voltage α at the moment of switching on the transformer depends on whether the unidirectional current exceeds the critical value of the I_c current of the HTS transformer winding and thus whether the winding will exit the superconducting state.

Numerical analysis

A single-phase superconducting transformer with a power of 13.8 kVA was analysed [6].

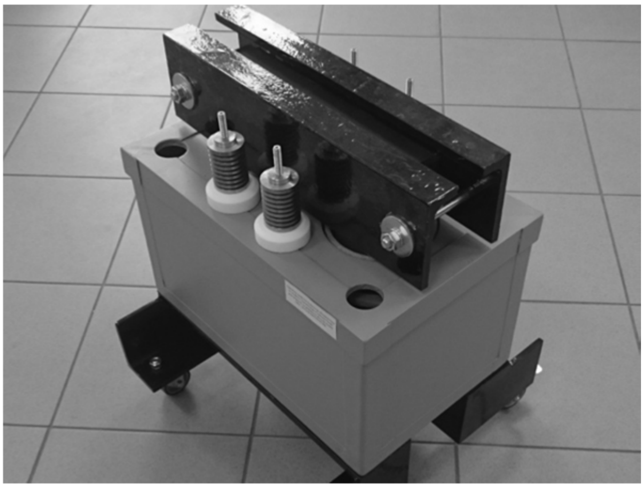

Fig. 2. 13.8 kVA superconducting transformer

Table. 1. Rated parameters

Parameter	TrHTS 13.8 kVA
Power	13.8 kVA
Frequency	50 Hz
HV/LV voltage	230 V/60 V
HV/LV current	60 A/230 A
I_c/I_n HV/LV ratio	1.44/1.44
Magnetic induction	1.6 T
Neutral current	0.7 A
Short circuit voltage	3.2%

Table. 3. Winding parameters

Parameter	TrHTS 13.8 kVA
Number of HV/LV coils	84/22
Material of HV and LV windings	Super Power (Re)BCO SCS4050-AP /SCS12050-AP
Critical current	87 A/333 A
Dimensions of HV and LV windings	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 (294K)	2.9 Ω/0.57 Ω
Resistance of HV/LV winding (77K)	$0.0466 \cdot 10^{-18}$ Ω $/0.0097 \cdot 10^{-18}$ Ω
Resistance of HV/LV winding after switching to resistive state (77K)	23 μΩ/5 μΩ
Inductance of HV/LV windings	290 μH/18 μH
Sectional area of HV winding	0.0244 m^2

The rated parameters of the transformer are given in Table 1 and the technical parameters of the superconducting windings are given in Table 2.

The dependence (1) shows that the angle θ and thus the maximum value of the inrush current depends on three inductions: the saturation induction of the B_n transformer core, the nominal maximum induction in the B_m core and the residual magnetism in the core at the moment of switching on the B_r transformer. Figure 3 shows the loop of the hysteresis of the transformer core under rated conditions. The maximum induction is 1.6 T, the maximum possible residual magnetism induction is 1.4 T and the saturation induction is 1.75 T.

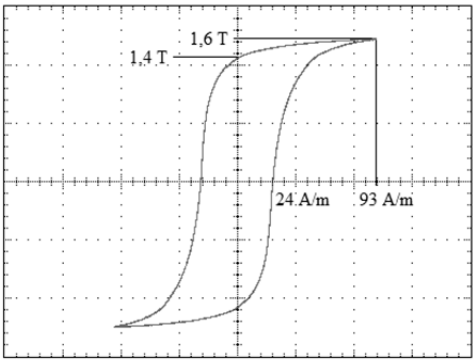

Fig. 3. Magnetic hysteresis of the HTS transformer core at rated operating conditions

The parameters of the HTS transformer given above were used in the calculation of the numerical analysis of the inrush current.

The dependencies (1) and (3) on the inrush current have been verified experimentally. The measurements were made when the unloaded HTS transformer of 13.8 kVA power was switched on. The switching was carried out in the least favourable conditions when the supply voltage passes through zero. To eliminate the random influence of the induction of residual magnetism, the transformer was switched on after demagnetizing the core. In the range of analysed inrush current pulse ranges, a good correlation between the measured and numerically obtained waveforms was obtained. Relative error did not exceed 1%.

The analysis shows that the HTS transformer windings of 13.8 kVA power come out of the superconducting state when the transformer is switched on in the range of phase angles of the supply voltage α ranging from 0° to 40° (Fig. 4 and 5). For this range of angles α, the unidirectional current pulse exceeds the value of critical current I_c of the windings, which for the transformer in question has the value of 87 A. For phase angles of voltage α equal to 50°, 60°, 70° and 80°, the unidirectional current pulse does not exceed the critical value of the current and the windings do not leave the superconducting state. For angle α equal to 90°, the unidirectional current pulse does not appear.

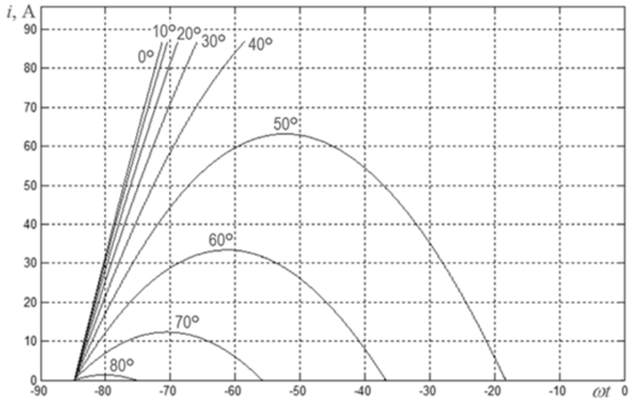

Fig. 4. Inrush current pulse ranges in which HTS transformer windings are in the superconductive state for different voltage phase angle values at the moment of switching on the transformer

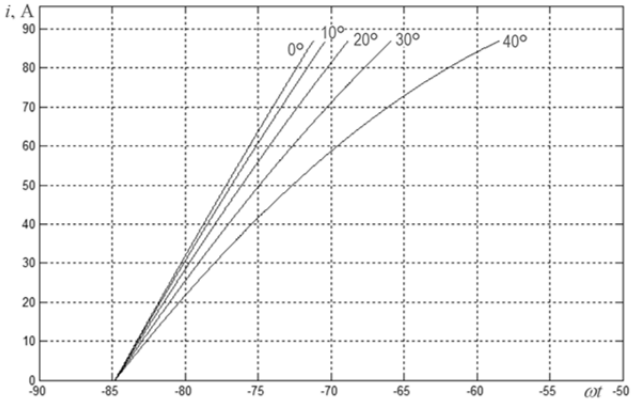

Fig. 5. Running of the rising edge of the unidirectional current pulse until the loss of the superconducting state of the HTS transformer windings

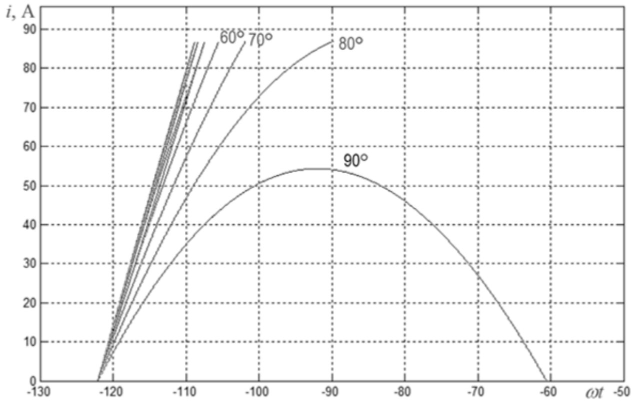

Fig. 6. Inrush current pulse ranges in which HTS transformer windings are superconducting for different voltage phase angle values at the moment of transformer switching on and residual magnetism induction equal to 1T

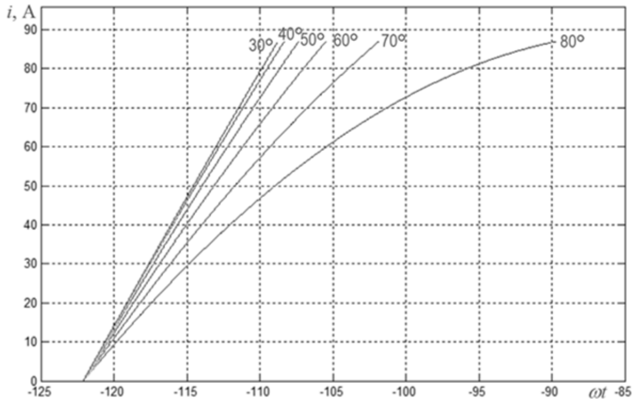

Fig. 7. Running of the rising edge of the unidirectional current pulse until the loss of superconductivity of the HTS transformer windings for a residual magnetism induction of 1T

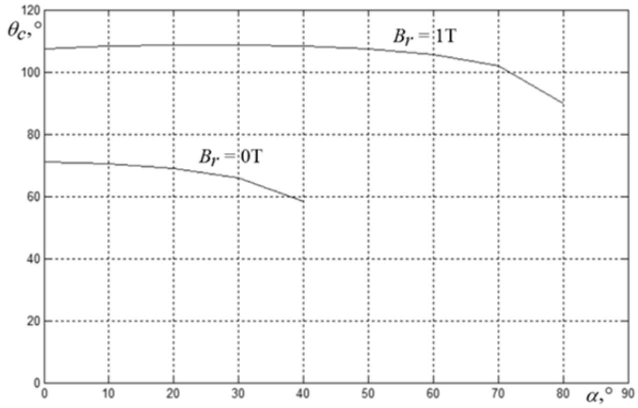

Fig. 8. Distribution of angles at which the superconductivity of the HTS transformer with a power of 13.8 kVA is lost

The angle θ_c at which the superconductivity of the HTS transformer windings is lost is 71,21° for the phase angle of voltage equal to 0°. For angle α=10° θ_c=70,4°, α=20° θ_c=68,82°, α=30° θ_c=65,83°, α=40° θ_c=58,44° (Fig. 5).

In most cases, the transformer is switched on at a certain value of residual magnetism in the core. Figures 6 and 7 show the range of one-way current pulses in which the HTS transformer windings do not come out of the superconducting state when the switch-on took place at the residual magnetism induction B_r=1 T.

If the switching on of the HTS transformer took place at the induction of residual magnetism equal to 1 T and the phase angle of voltage α=90° then during the entire impulse of the unidirectional current the windings do not leave the superconducting state. The loss of superconductivity will take place for angles α smaller than 80°. The angle θ_c at which the loss of superconducting state takes place is 89.7° for α=80° and θ_c=101,82° for α=70°, θ_c=105,48° for α=60°, θ_c=107,35° for α=50°, θ_c=108,34° for α=40° and θ_c=108,77° for α=30° (Fig. 7).

The distribution of variability of the angle of loss of superconducting state of θ_c windings as a function of the phase angle of voltage at the moment of switching on the HTS α transformer for different values of residual magnetism induction in the B_r transformer core is shown in Figure 8.

Summary

The derived dependency on the inrush current of the HTS (3) transformer with a good approximation describes the course of this current when the windings are in the state of superconducting. The relative error between the measured and calculated value does not exceed 1%. The numerical analysis carried out for the HTS transformer with a power of 13.8 kVA shows that the value of the phase angle of voltage at the moment of switching on the transformer significantly affects the loss of the superconducting state of the windings. When the transformer is switched on at zero value of residual magnetism induction in the core, the loss of superconductivity of the windings takes place at phase angles of voltage in the range of 0°÷40°. In the case when the switch-on occurs at the residual magnetism induction equal to 1 T, the range of phase angles of voltage at which the loss of superconductivity of the windings occurs increases and covers the range 0°÷80°. Knowledge of these angles allows to estimate, by measuring the phase angle of voltage at the moment of switching on the HTS transformer, whether its windings will come out of the superconductivity state. Such a state should be treated as an emergency state which makes it difficult to switch on the HTS transformer and threatens to cause thermal damage to its windings.

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