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Impact of HTS transformer magnetic circuit parameters on the duration of the inrush current pulse

Streszczenie. *Utratę stanu nadprzewodzenia uzwojeń transformatora nadprzewodnikowego traktuje się jako stan awaryjny grożący termicznym uszkodzeniem ciągłości obwodu. 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. Głównym czynnikiem decydującym o przebiegu fali prądu włączania jest kształt pętli histerezy rdzenia transformatora. W pracy przeanalizowano wpływ podstawowych parametrów magnetycznych rdzenia na przebieg impulsu prądu włączania transformatora nadprzewodnikowego ze zwróceniem uwagi na zjawisko utraty stanu nadprzewodzenia uzwojeń. (**Wpływ parametrów obwodu magnetycznego transformatora HTS na czas trwania impulsu prądu włączania**).*

Abstract*. Loss of superconducting state of the superconducting transformer windings shall be treated as an emergency state threatening thermal failure of the circuit continuity. 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. The main factor determining the inrush current waveform is the shape of the hysteresis loop of the transformer core. The paper analyses the influence of the basic magnetic parameters of the core on the pulse of the inrush current of the superconducting transformer with attention paid to the phenomenon of the loss of the superconducting state of the windings.*

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

Introduction

Every sudden change of voltage at the transformer terminals is accompanied by a transient state. This state occurs after the transformer is switched on, as well as after voltage drops and power supply interruptions. The transient state results in a inrush current that is many times the rated current of the transformer. The phenomenon of inrush current of transformers with copper or aluminium windings is relatively well recognized, yet it still causes many operating problems. In the case of superconducting transformers (HTS), this phenomenon is poorly recognized [1]. The value of inrush current can be many times higher than the rated current of the transformer and thus the critical value of the current of superconducting windings. When the HTS transformer is switched on, its windings may lose their superconducting state, which makes it difficult to connect the transformer to the mains, creating the risk of thermal damage and breaking the continuity of windings. The loss of superconductivity is accompanied by a rapid increase in the temperature of the superconducting cable according to the law of Joule-Lenz. The temperature of a resistive superconducting cable can reach significant values due to the high current densities typical of this type of cable. This temperature depends on the electrical, thermal and structural parameters of the HTS transformer windings and the duration of the inrush current that has led to the loss of superconductivity.

The value and time of decay 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. The influence of magnetic parameters of the HTS transformer core on the duration of the inrush current pulse was analyzed.

The inrush current

The inrush current has two components: fixed and disorderly [2] The fixed component is a periodically alternating no-load current, which is supplied from the mains supply to excite the flux in the core and to cover the power losses in the transformer in the fixed state of its operation. The disruption component is an aperiodic current, which is a one-way current impulse that appears at the moment of saturation of the transformer core and disappears when the core returns to normal operation.

The value and course of the inrusch current is influenced by the magnetization curve in the area of transformer core saturation [3][4]. Knowing the time course of the flux, it is possible to graphically determine the time course of the switching current on the basis of the magnetization characteristic Φ=f(I_0) (Fig. 1).

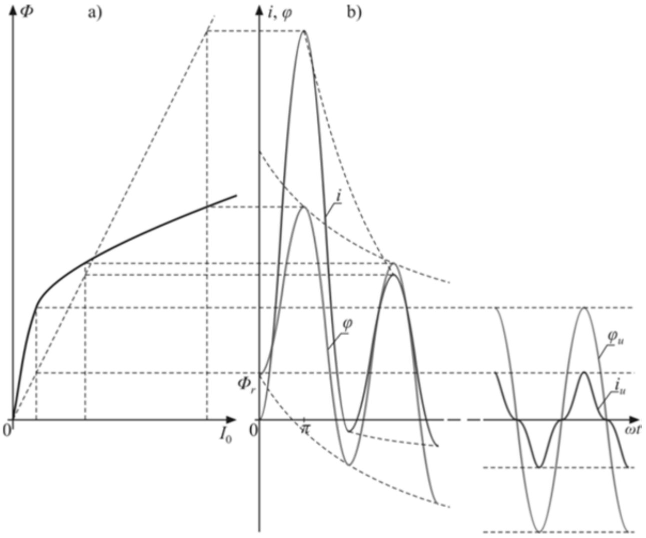

Fig. 1. Graphical determination of the inrush current: a) magnetization characteristics, b) time course of the flux and current

The substitution diagram for a single-phase HTS transformer in idle state does not differ from the conventional transformer diagram. The difference is reduced to the non-linear resistance of the winding R_1 with the value depending on the state of the superconducting wire (Fig. 3).

The proper operating state of the HTS transformer windings is the superconducting state. In the superconducting state (interval I and III in Fig. 3) the real 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_1=0).

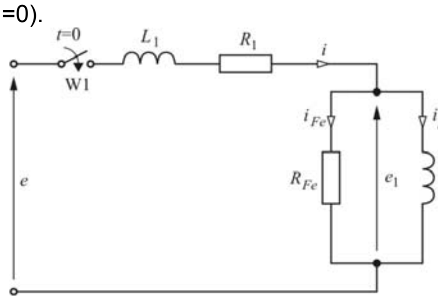

Fig. 2. Diagram of a single-phase transformer in idle state

The transformer windings go to a resistive state when the momentary inrush current exceeds the critical current I_c of the HTS cable (interval II in Fig. 3) [5], when the winding temperature exceeds the critical temperature T_c of the cable or when the external magnetic field strength exceeds the critical value H_c. The resistance of the windings then increases rapidly to the value typical for a given type of HTS cable.

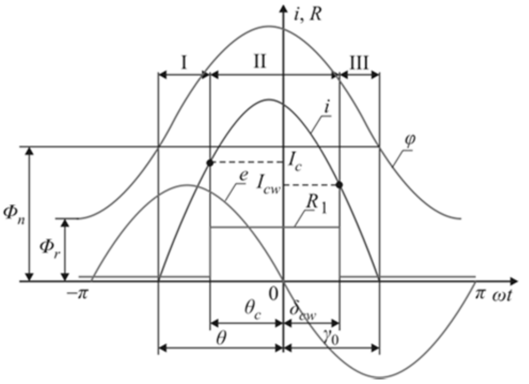

Fig. 3. Plots: i - pulse of unidirectional current, φ - flux in transformer core, R_1 - resistance of HTS winding, e - supply voltage

Excluding the active component of current to cover losses in iron (R_{Fe}=∞) and assuming that the substitution impedance is the sum of the inductance L_1 associated with the scattering flux and the inductance L_μ associated with the main flux (L=L_μ+L_1) and the substitution resistance R is the sum of the resistance of the primary winding R_1 and the resistance R_{Fe} representing the losses in the magnetic core resulting from hysteresis and eddy currents (R=R_1), the basic equation of transformer operation can be written as (1):

$$-\sqrt{2}Esin(\omega t+\alpha)=z\Phi\frac{R}{L}+z\frac{d\Phi}{dt} \tag{1}$$

where: E - the source voltage, ω - pulsation, α - phase angle of voltage, z - the number of primary winding windings, Φ - magnetic flux.

After the integration of equation (1) the expression for flux is obtained (2):

$$\begin{gathered}\varphi=-\Phi_m sin(\omega t+\alpha-\delta)\\ -\Phi_m sin(\pi-\alpha+\delta)e^{-\frac{R}{X}(\pi+\omega t)}+\Phi_r e^{-\frac{R}{X}(\pi+\omega t)}\end{gathered} \tag{2}$$

where Φ - the maximum magnetic flux, δ - the phase shift angle is equal (3):

$$\delta=arctg\frac{X}{R} \tag{3}$$

Depending on the relation (2), the magnetic flux φ reaches its highest value after switching on the transformer. This value depends on the phase angle of the supply voltage e and the value of the residual magnetism flux Φ_r at the moment of switching on the transformer and the value of the R/X ratio of the electrical circuit.

As can be seen from relation (2), the residual magnetism flux has a significant influence on the value and method of flux determination φ. In high power transformers, the residual magnetism flux can reach up to 80% of the rated flux, depending on the type of plate used, the construction of the core, its dimensions, the quality of the assembly, the flux value at the time the transformer is switched off and the time elapsed since it was switched off.

If the transformer is switched on in the most convenient conditions, when the supply voltage e reaches its maximum value, i.e. for angle $\alpha=-\pi/2$, the flux φ described by the expression (2) reaches its maximum value (Fig. 4a)(4):

$$\Phi_M=\Phi_m+\Phi_r \tag{4}$$

The expression (2) reaches the highest value when the transformer is switched on at the moment when the voltage e passes through zero, i.e. for angle $\alpha=-\pi$. Then the flux φ associated with the primary winding reaches the maximum value (Fig. 4b) (5):

$$\Phi_M=2\Phi_m+\Phi_r \tag{5}$$

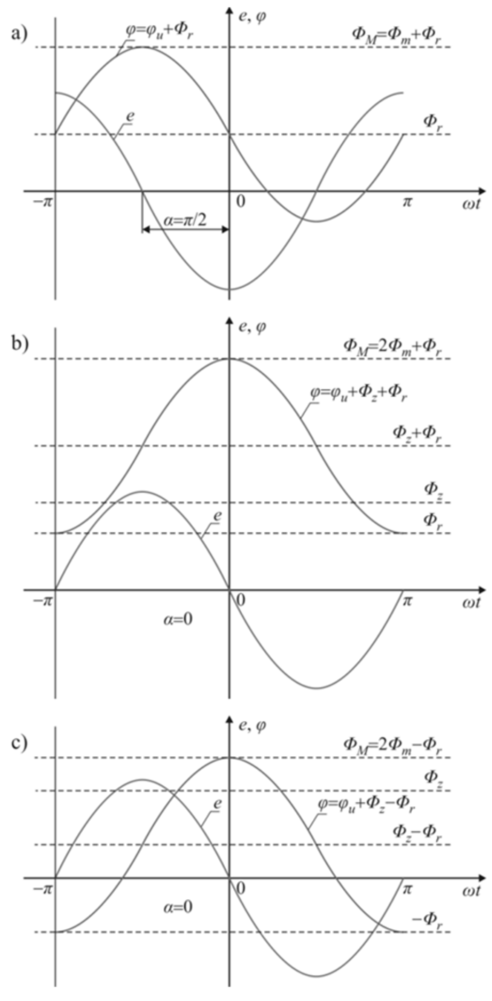

Fig. 4. Flux changes after switching on the transformer: a) switching on when the voltage reaches the maximum value, b) switching on when the voltage passes through zero, c) switching on when the voltage passes through zero and when residual magnetism is negative.

The residual magnetism flux can also reduce the peak value of the flux. If the residual magnetism flux Φ_r has negative polarity at the moment of switching on the transformer and the transformer is switched on in the least favourable conditions, the flux φ given by the expression (2) reaches the maximum value (Fig. 4c) (6):

$$\Phi_M = 2\Phi_m - \Phi_r \tag{6}$$

If the resistance of the circuit (R=0) and the active component of the current to cover losses in iron are omitted, then in the steady state the flux in the core of the HTS transformer will be delayed by an angle of $\delta=\pi/2$. Assuming additionally that the phase angle of voltage α is equal to zero, it results from equation (2) that the one-way current impulse appears when the momentary value of the flux φ exceeds the value of the induction flux of the core saturation Φ_n, which takes place for $\omega t=-\theta$ (Fig. 3) and the angle is given by the relation (7):

$$\cos\theta = \frac{B_n - B_m - B_r}{B_m} \tag{7}$$

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.

By solving the equations describing the circuit from Fig. 2, the equation for unidirectional current is obtained due to the current (8):

$$(8) i = -\frac{E_m X_1}{Z_1^2}\left[\frac{R_1}{X_1} sin(\omega t + \alpha) - cos(\omega t + \alpha) - \left(\frac{R_1}{X_1} sin(\alpha - \theta) - cos(\alpha - \theta)\right) e^{-\frac{R_1}{X_1}(\omega t + \theta)}\right]$$

where: X_1 - circuit reactance, Z_1 - circuit impedance.

Equations (2), (7) and (8) allow to plot the course of the inrush current in the range from the moment the transformer is switched on to the moment when the HTS windings come out of the superconducting state. On the basis of these equations it is possible to determine the time after which from the moment the transformer is switched on the impulse of the unidirectional current will appear and the time after which from the moment the impulse of the unidirectional current the HTS winding will come out of the superconducting state.

Transformator HTS

A single-phase HTS transformer with a power of 13.8 kVA (Fig. 5) was tested and numerically analyzed [6]. The parameters of the transformer are given in Table 1.

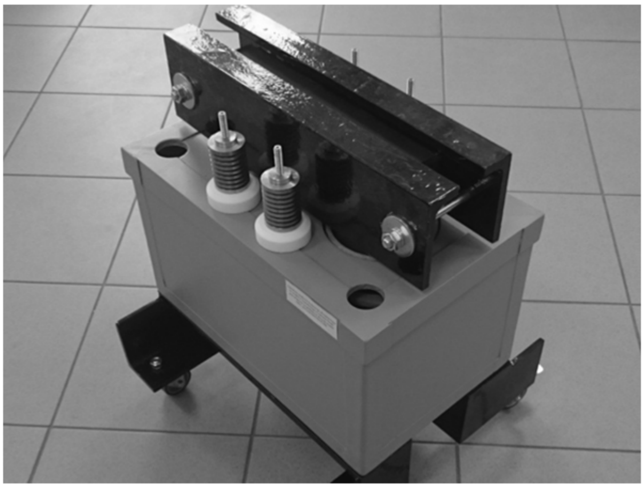

Fig. 5. 13.8 kVA superconducting transformer

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%

The transformer core is made as bevelled and stepped, in the sheet metal cutting system 4, 3, 1. The core material is an electrotechnical transformer sheet with grain oriented orientation, meeting the requirements of EN 10107:2005. Material designation M150-30S. Metal sheet thickness 0.3 mm, silicon content in steel 3%, maximum total loss at 50 Hz and induction 1.5 T is 0.97 W/kg and 1.5 W/kg at 1.7 T, minimum magnetic induction 1.75 T at H=800 A/m. The core hysteresis loop plotted from the measurements is shown in Figure 6. The residual magnetism induction for the core is 1.4 T, which is 87% of the nominal induction.

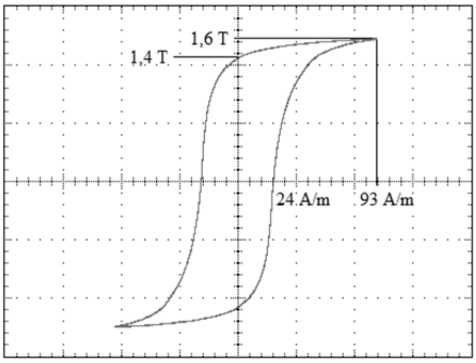

Fig. 6. Magnetic hysteresis of the HTS transformer core at rated operating conditions

Analiza numeryczna

Numerical analysis was carried out in the range from the angle $-\pi$ (Fig. 3) for which the HTS transformer is switched on to the angle $-\theta_c$ for which the HTS winding comes out of the superconducting state.

It results from the dependence (7) that the angle θ calculated from the moment the transformer is switched on until the moment the unidirectional current pulse appears is a function of three quantities:

$\theta=f(B_n, B_m, B_r)$

The graph of angle θ variability is shown in Figure 7. Under rated operating conditions of a 13.8 kVA HTS transformer, the angle θ changes according to the curve B_m/B_n=0.9. For the highest value of residual magnetism induction at the moment of switching on the HTS transformer equal to 1.4 T, i.e. Br/Bm=0.87, the angle θ reaches the value of 141°. At zero residual magnetism induction, the angle is 83.6°.

For the operation of the HTS transformer it is important to know the angle at which the windings come out of the superconducting state. From equation (8) it follows that this angle is a function of two quantities:

$\theta_c=f(\theta, \alpha)$

Figure 8 shows changes of θ_c angle in the function of B_r/B_m ratio for rated induction in the core, i.e. B_m/B_n=0.9, for selected values of voltage phase angle α.

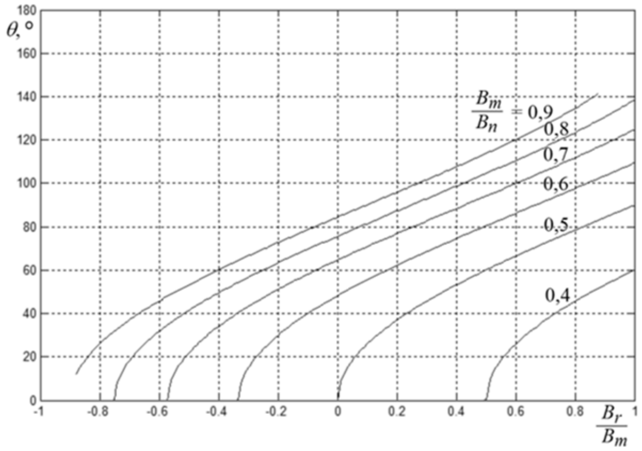

Fig. 7. Angle value depending on B_r/B_m ratio value for selected B_m/B_n values

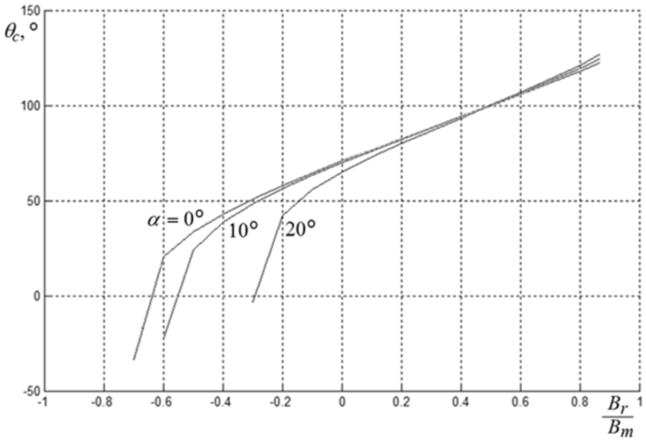

Fig. 8. Value of the angle c depending on the value of the ratio B_r/B_m and B_m/B_n==0.91 for selected values of the angle

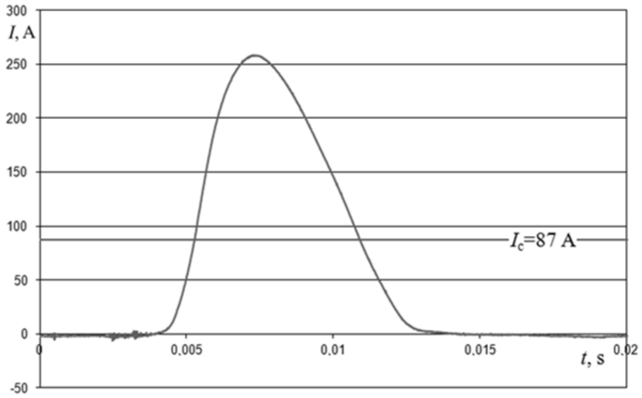

Fig. 9. Measured waveform of the first unidirectional current pulse

The θ_c angle reaches the highest value of 126.8° for the highest residual magnetism induction value at the moment of switching on the HTS transformer equal to 1.4 T when the switching takes place at a phase shift of voltage equal to 20°. When the switch-on occurs under the same conditions but when the voltage passes through zero, the angle is 122.6°. Within the range of B_r/B_m variations from 0 to 0.87, the differences in the value of the angle θ_c are insignificant and do not exceed several degrees. The biggest differences are recorded for negative values of B_r/B_m ratio between -0.7 and 0, i.e. for inrush current pulses of short duration.

The actual course of the first pulse of the 13.8 kVA HTS transformer inrush current is shown in Figure 9. The pulse was obtained when the transformer was switched on when the voltage passes through zero and the magnetic induction value in the core is zero.

Summary

The presented numerical analysis allows to easily determine the basic parameters of the inrush current pulse from the moment the HTS transformer is switched on to the moment the windings leave the superconducting state. This allows at the stage of designing the HTS transformer to determine whether the superconducting state of the windings will be lost during its switching on and when it will take place. The results of numerical analysis showed good compliance with the results of measurements with the relative error of 1% for the first current pulse.

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