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SYNTHESIS ASPECTS OF CRYOGENIC HIGH-TEMPERATURE SUPERCONDUCTING SHIELDING INDUCTIVE SHORT-CIRCUIT CURRENT LIMITER

The short-circuit current limiter of inductive type with the high-temperature superconducting winding and screen is considered. The basic design parameters of the magnetic system were determined and features of the transition process at the initiation of short-circuit were analyzed.

Key words: short-circuit, current limiter, high temperature superconductor, ferromagnetic core.

Розглянуто обмежувач струму короткого замикання індуктивного типу з високотемпературними надпровідними обмоткою та екраном. Визначено основні конструктивні параметри магнітної системи і проаналізовано особливості перехідного процесу при виникненні струму короткого замикання.

Ключові слова: *коротке замикання, обмежувач струму, високотемпературний надпровідник, магнітопровід.*

Рассмотрен ограничитель тока короткого замыкания индуктивного типа с высокотемпературными сверхпроводящими обмоткой и экраном. Определены основные конструктивные параметры магнитной системы и проанализированы особенности переходного процесса при возникновении тока короткого замыкания.

Ключевые слова: *короткое замыкание, ограничитель тока, высокотемпературный сверхпроводник, магнитопровод.*

Introduction. Limiting short-circuit currents are quite actual problem as fault regimes that lead to equipment failure of electrical systems and power stations and can require later their removal and replacement.

The use of such device as superconducting short-circuit current limiter (SCCL) with low-temperature superconducting elements have no broad application because of expensiveness of liquid helium. Only with occurrence of the high-temperature superconducting (HTSC) materials cooled at temperature of liquid nitrogen (77 K), the different constructions of SCCL have been created. They can be divided into two basic groups: resistive and inductive [1].

Analysis of the SCCL. The constructive scheme of inductive SCCL with the HTSC screen, HTSC winding and magnetic core is shown in fig. 1. Whole magnetic system is immersed into cryostat [2].

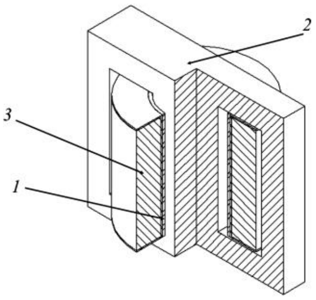


Fig. 1 – The constructive scheme of inductive SCCL: *1* – superconducting screen, *2* – magnetic core, *3* – superconducting winding

Analysis of the proposed inductive superconducting current limiter to determine the main parameters and mathematical model of transient short-circuit is a very important task.

The nominal current I_n flows throw HTSC winding *3* connected in series with load. At normal operation (nominal parameters) the magnetic induction B_s created by the winding *3* is less than its critical value of the magnetic induction B_{sc} for HTSC screen *1* and magnetic field will not penetrate into the core *2*.

At short-circuit the current in a HTSC winding *3* starts to increase and reaches value at which intensity of a magnetic field for the HTSC screen *1* becomes critical H_{cr}. The HTSC screen loses superconducting properties at achievement on its surface value of critical magnetic induction B_{sc} and it ceases to shield a magnetic flux. The magnetic flux penetrates into the magnetic core *2*, inductance of SCCL repeatedly increases, that results in limiting of the fixed value of short-circuit current.

SCCL is intended for an electric grid with nominal parameters: total power S_n, voltage U_n, current I_n. The HTSC wire tape [3] with width a_w and thickness b_w can be used for a winding. Its critical current i_{cr} should be 4–5 times more than nominal current I_n. The cross section of a superconductor is much less than cross section of a substrate, therefore in a zone of HTSC winding it is possible to take the relative magnetic permeability $\mu_r = 1$ [4].

The magnetic induction on a surface of superconducting screen B_s should be 2,5–3 times smaller than critical value B_{sc}. This magnetic induction determines number of rows of a superconducting winding by

$$n = \frac{B_s \cdot a_w}{\mu_0 \cdot I_n}. \qquad (1)$$

The number of wires in row of winding is equal to:

$$m = h / a_w, \qquad (2)$$

where *h* is the height of the superconducting screen and winding.

The total number of conductors of a superconducting winding is:

$$w = \frac{B_s \cdot h}{\mu_0 \cdot I_n}. \qquad (3)$$

Considering that winding of SCCL keeps a superconducting condition both under nominal operation, and at short-circuit, it is possible to assume, that the voltage applied to it goes on compensation of electromotive force of a self-induction. At preservation of a superconducting condition of a winding the active component of a voltage drop cross it is neglible. Therefore the voltage drop cross SCCL at normal operation is characterized by voltage coefficient k_{CL} as follows:

$$U_{CL} = k_{CL} \cdot U_n = 4{,}44 f \cdot w \cdot \Phi, \qquad (4)$$

where *f* is the frequency; Φ is the magnetic flux linked to a superconducting winding.

At first approximation the thickness of the HTSC screen can be leave out of owing to its smallness thus $r_{mw} = r_{rod}$ and magnetic flux can be evaluated:

$$\Phi = B_s \pi \cdot r_{rod} \cdot n \cdot b_w . \qquad (5)$$

At short-circuit the superconducting winding is under rated voltage

$$U_n = 4{,}44 f \cdot w \cdot B_{mc} \cdot \pi \cdot r_{rod}^2 . \qquad (6)$$

The magnetic induction B_{mc} of flux penetrated into an average rod of the magnetic core should correspond to average zone of B-H curve saturation. Otherwise the increase of short-circuit current will result in oversaturation of the magnetic core.

Comparing a voltage drop U_{CL} cross SCCL and nominal voltage U_n the dependence of radius of an average rod of magnetic core on voltage coefficient k_{CL} can be obtained as:

$$r_{rod} = \frac{B_s \cdot n \cdot b_w}{k_{CL} \cdot B_{mc}} . \qquad (7)$$

It is possible to find the dependence of volumes of the magnetic core and a superconducting winding on voltage coefficient k_{CL}. Assuming on that at short-circuit the magnetic induction in the magnetic core is identical on all its pats, the volume of magnetic core V_{cr} is equal to the sum of volumes of two average rods of magnetic core and two yoke connections their total cross section is equal to cross section of an average rod of magnetic core:

$$V_{cr} = \pi \cdot r_{rod}^2 \left(2h + A\right). \qquad (8)$$

The height of the screen h can be found from the expression (6), substituting the number of turns of a superconducting winding by formula (3):

$$h = \frac{\mu_0 \cdot S_n}{2\pi^2 f \cdot B_s \cdot B_{mc} \cdot r_{rod}^2} . \qquad (9)$$

Substituting in (8) $r_{\text{ст}}$ and h, also specifying with a sufficient degree of accuracy that $A = 4r_{rod}$, the volume of magnetic core expressed by:

$$V_{cr} = \frac{\mu_0 \cdot S_n}{\pi \cdot f \cdot B_s \cdot B_{mc}} + \frac{4\pi}{k_{CL}^3} \left(\frac{B_s \cdot n \cdot b_w}{B_{mc}} \right)^3 . \qquad (10)$$

The volume of superconducting winding V_{sw} is determined by number of turns multiplied into their average length and into cross section of a wire:

$$V_{sw} = \frac{\mu_0 \cdot S_n \cdot k_{CL}}{\pi \cdot f \cdot B_s^2} . \qquad (11)$$

Thus, it is possible to determine the basic design parameters of SCCL proceeding from critical parameters of superconducting winding and screen. Comparison of volumes of magnetic core and winding gives a possibility to choose their parameters [5].

Considering the transient process in circuit with SCCL under normal operation, the current of load I_n is defined by nominal voltage U_n and impedance of load Z_l. Taking into account that the voltage drop across the SCCL does not exceed 3–5 % of U_n and nature of a voltage drop is only inductive, it is possible to consider, that $I_n = U_n / Z_l$. Thus the initial condition at the moment of short-circuit initiation is:

$$i_{n0} = I_{nm} \sin\left(\psi_u - \varphi_l\right), \qquad (12)$$

where $I_{nm} = U_{nm} / Z_l$ is the amplitude of load nominal current; ψ_u is the initial phase of short-circuit; φ_l is the phase angle of load.

The transient process becomes complicated because at increase of short-circuit current flowing through the SCCL, the intensity of magnetic field on the surface of HTSC screen increases up to its critical value H_{cr}, the screen loses its superconducting properties, also the superconductivity of a HTSC winding can be lost when the current achieves critical value i_{cr}. Both the first and the second circumstances change the inductance of the current limiter and the resistance of its winding, this results in changing of the time constant and impedance of the SCCL.

All above-stated gives the basis to divide transient process in SCCL at short-circuit into three stages in two variants [6]:

1) from an initial current expressed by (12) to loss of superconducting properties of HTSC screen (or to loss of superconductivity of HTSC winding);

2) from loss of superconducting properties of HTSC screen to loss of superconductivity of HTSC winding (or on the contrary from loss of superconductivity of HTSC winding to loss of superconductivity of HTSC screen);

3) from loss of all effects of superconductivity to the fixed limiting current in electric grid.

Realization of the first or second variants is defined by selection of HTSC materials for the screen and winding, accordingly their critical parameters.

The induction of magnetic field on the surface of HTSC screen B_s is defined by a current and the number of rows n of HTSC winding. Therefore, knowing critical magnetic induction B_{cr} for HTSC material of the screen, it is possible to realize the first variant, when the number of rows of HTSC winding is n and B_{cr} reaches at i_{cr} = (2,5–3) I_{nm}. Thus the critical value of current should be i_{cr} = (4–5) I_{nm}, this guarantees normal operation of SCCL at potential fluctuations of current in the electric grid.

The second variant occurs if the critical value of current i_{cr} is equal to (2,5–3) I_{nm}, and B_{cr} for the screen reaches at current (4–5) I_{nm}.

The first stage is identical to both variants. Its parameters are following: R_{CL1} is the resistance of HTSC winding, L_{CL1} is the inductance of the current limiter and $Z_{CL1} = \sqrt{R_{CL1}^2 + \left(\omega L_{CL1}\right)^2}$ is the impedance of current limiter, where $\omega = 2\pi f$ – angular frequency.

The resistance of HTSC winding is

$$R_{CL1} = P_0 / I_n^2 , \qquad (13)$$

where P_0 is the total losses in a superconducting winding.

Substituting B_s by (1) into expression (5) linked to w in ratio to I_n we obtain the inductance of the SCCL as:

$$L_{CL1} = \mu_0 n^2 w \frac{b_w}{a_w} \pi r_{rod} , \qquad (14)$$

where w is the number of turns in HTSC winding; a_w is the width of tape wire; b_w is the thickness of tape wire.

At the first stage the solution can be presented as $i_{cr1} = i_{fix1} + i_{fr1}$, where fixed current $i_{fix1} = \frac{U_{nm}}{Z_{CL1}} \sin\left(\omega t + \psi_u - \varphi_{CL1}\right)$ and the free component i_{fr1} is determined by the differential equation $L_{CL1} \frac{di_{fr1}}{dt} + R_{CL1} i_{fr1} = 0$, that gives in a general form

$i_{fr1} = A_1 e^{-\frac{R_{CL1}}{L_{CL1}}t}$.

Then $i_{cr1}(t) = \frac{U_{nm}}{Z_{CL1}}\sin(\omega t + \psi_u - \varphi_{CL1}) + A_1 e^{-\frac{R_{CL1}}{L_{CL1}}t}$,

where $\varphi_{CL1} = \operatorname{arctg}\frac{\omega L_{CL1}}{R_{CL1}}$.

From initial condition the constant of integration is $A_1 = I_{nm}\sin(\psi_u - \varphi_l) - \frac{Un_m}{Z_{CL1}}\sin(\psi_u - \varphi_{CL1})$.

Accordingly, the initial phase of voltage for the second stage of transient process increases by ωt_{cr1}, in particular the solution in a general form is as follows:

$$i_{cr2}(t) = \frac{U_{nm}}{Z_{CL2}}\sin[\omega(t + t_{cr1}) + \psi_u - \varphi_{CL2}] + A_2 e^{-\frac{R_{CL2}}{L_{CL2}}t},$$

where readout relative to time t begins from zero: $0 \le t \le t_{cr2}$, where t_{cr2} is the time of the second stage end. From initial condition for the second stage at $t = 0$ $i_{cr2} = k_{i1}I_{nm}$ (k_{i1} = 2,5–3) we determine $A_2 = k_{i1}I_{nm} - \frac{U_{nm}}{Z_{CL2}}\sin(\omega t_{cr1} + \psi_u - \varphi_{CL2})$.

At the third stage its initial condition is $i_{cr3} = k_{i2}I_{nm}$ (k_{i2} = 4–5) at $t = 0$ where readout of time t starts from zero: $0 \le t \le t_{cr3}$ (t_{cr3} is the third stage end). The initial phase of voltage increases by ωt_{cr2}, and the solution has a general form:

$$i_{cr3}(t) = \frac{U_{nm}}{Z_{CL3}}\sin[\omega(t + t_{cr1} + t_{cr2}) + \psi_u - \varphi_{CL3}] + A_2 e^{-\frac{R_{CL3}}{L_{CL3}}t}.$$

From initial condition for the third stage it is determined $A_3 = k_{i2}I_{нm} - \frac{U_{нm}}{Z_{CL3}}\sin[\omega(t_{cr1} + t_{cr2}) + \psi_u - \varphi_{CL3}]$.

Thus the transient process of the current at short-circuit can be described by system of equations

$$\begin{cases} i_{cr1}(t) = \frac{U_{nm}}{Z_{CL1}}\sin(\omega t + \psi_u - \varphi_{CL1}) + \\ + \left[I_{nm}\sin(\psi_u - \varphi_l) - \frac{U_{nm}}{Z_{CL1}}\sin(\psi_u - \varphi_{CL1})\right] e^{-\frac{R_{CL1}}{L_{CL1}}t}; \\ i_{cr2}(t) = \frac{U_{nm}}{Z_{CL2}}\sin[\omega(t + t_{cr1}) + \psi_u - \varphi_{CL2}] + \\ + \left[k_{i1}I_{nm} - \frac{U_{nm}}{Z_{CL2}}\sin(\omega t_{cr1} + \psi_u - \varphi_{CL2})\right] e^{-\frac{R_{CL2}}{L_{CL2}}t}; \\ i_{cr3}(t) = \frac{U_{nm}}{Z_{CL3}}\sin[\omega(t + t_{cr1} + t_{cr2}) + \psi_u - \varphi_{CL3}] + \\ + \left[k_{i2}I_{nm} - \frac{U_{nm}}{Z_{CL3}}\sin[\omega(t_{cr1} + t_{cr2}) + \psi_u - \varphi_{CL3}]\right] e^{-\frac{R_{CL3}}{L_{CL3}}t}, \end{cases} \qquad (15)$$

where SCCL parameters of transient process: second stage: first variant – $R_{CL2} = R_{CL1}$; $L_{CL2} = \frac{wB_{mc}\pi r_{rod}^2}{k_{i1}I_{nm}}$; $Z_{CL2} = \sqrt{R_{CL1}^2 + (\omega L_{CL2})^2}$; $\varphi_{CL2} = \operatorname{arctg}\frac{\omega L_{CL2}}{R_{CL1}}$; second variant – $R_{CL2} = \rho_w\frac{w2\pi r_{rod}}{S_w}$; $L_{CL2} = L_{CL1}$; $Z_{CL2} = \sqrt{R_{CL2}^2 + (\omega L_{CL1})^2}$; $\varphi_{CL2} = \operatorname{arctg}\frac{\omega L_{CL1}}{R_{CL2}}$; third stage – $R_{CL3} = \rho_w\frac{w2\pi r_{rod}}{S_w}$; $L_{CL3} = \frac{wB_{mc}\pi r_{rod}^2}{k_{i2}I_{nm}}$; $Z_{CL3} = \sqrt{R_{CL3}^2 + (\omega L_{CL3})^2}$; $\varphi_{CL3} = \operatorname{arctg}\frac{\omega L_{CL3}}{R_{CL3}}$.

Calculations of SCCL inductance can be spent by program FEMM in plane-parallel equivalent model. The magnetic flux is proportioned symmetrically on sections had along an axis "x" between HTSC screen and winding in a positive allowance δ_g and becomes isolated on a magnetic circuit (fig. 2), and also – on axis "y" sections lengthways organising leakage fluxes.

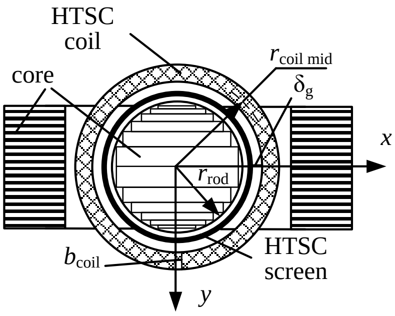
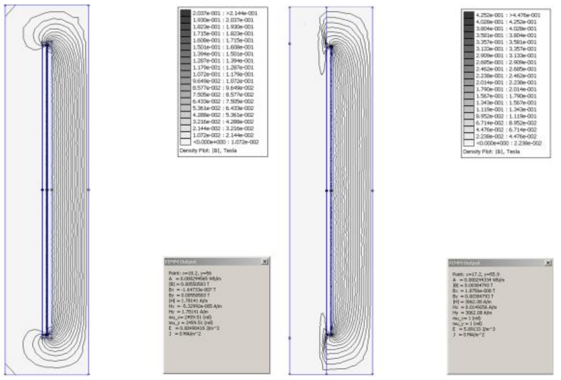


Fig. 2 – Cross-section of SCCL

On fig. 3 the geometry of build-up of the equivalent model SCCL in FEMM and allocation of magnetic field SCCL is resulted. The geometrical model recreates real magnetic core with such assumption that cross section of SCCL the right-angled, and magnetic flux allocation radially does not vary.



a *b*

Fig. 3 – Rated distribution of magnetic field of SCCL at the nominal regime along axis "x" (a) along axis "y" (b)

Diamagnetic properties to the superconducting screen are set by boundary conditions of Dirichlet – a vector potential on a surface to screen $A = 0$. Defining in the nominal regime is the magnitude of voltage drop on a current limiter, a magnetic flux induction near screen band which will spot power losses in a winding, and electromagnetic pressure on the screen.

The mathematical model of electromagnetic transient which consists of three stages, in an emergency operation of the electric circuit with a superconducting current limiter is presented by system of equations (15) which consider a modification of parameters of the electric circuit depending on sequence of loss superconductivity of the shield and a winding. On fig. 4 analytical dependence of a current for the first variant of transient when at the second stage superconductivity of the shield is lost at a short-circuit initial phase is presented $\psi_u = 0$ and $\psi_u = \pi/2$.

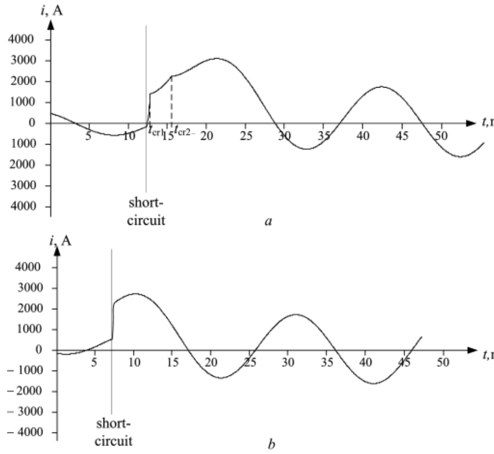


Fig. 4 – First variant of transient process at initial phase $\psi_u = 0$ (*a*) and $\psi_u = \pi/2$ (*b*)

Conclusions. The method of calculation basic parameters of the magnetic system of superconducting short-circuit current limiter is based on consideration of the coefficient voltage drop k_{CL}, allows selection of parameters in compliance grid and the critical parameters of superconductors.

Mathematical model of transient which consider the design features and capabilities of second-generation superconductors in electrical circuit during short-circuit and limiting current by inductive limiter constraint that considers crush circuit parameters depending on the sequence of losing the superconducting properties by screen and winding that is connected with their critical parameters is improved.

The duration of time transition t_{cr} to a greater extent depends on the moment of short-circuit, the slowest at $\psi_u = 0$. At the first and second stages of transient process, the duration of time t_{cr1}, t_{cr2} transition decreases depending on an initial phase of short-circuit at the shortest time $\psi_u = \pi/2$ which is less ms for second variant. The duration of the third stage of transient process depends on wire resistance R_{CL} of HTSC winding in normal state [7]. When the winding losses superconductivity, SCCL provides to the electric circuit the active resistance, which reduces current and time constant at the third stage of the transient process after the loss of superconductivity of screen for easy operation of protection apparatus.

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