APPLIED PHYSICS

ANALYSIS OF ENERGY EFFICIENCY OF A SUPERCONDUCTING SHORT CIRCUIT CURRENT LIMITER

Розроблено конструктивну схему обмежувача струму короткого замикання індуктивного типу з високотемпературними надпровідними обмоткою і екраном з повним кріогенним охолодженням магнітної системи. Запропоновано методику розрахунку втрат потужності і проведений аналіз енергоефективності обмежувача струму з кріогенним охолодженням магнітної системи з осердям. Отримані результати експериментально-теоретичного моделювання на макеті обмежувача струму з кріогенним охолодженням магнітної системи, які підтверджують підвищення енергоефективності розробленого конструктивно-технічного рішення

Ключові слова: обмежувач струму, високотемпературний надпровідник, екран, обмотка, магнітопровід, коротке замикання, втрати потужності

Разработана конструктивная схема ограничителя тока короткого замыкания индуктивного типа с высокотемпературными сверхпроводящими обмоткой и экраном с полным криогенным охлаждением магнитной системы. Предложена методика расчета потерь мощности и проведен анализ энергоэффективности ограничителя тока с криогенным охлаждением магнитной системы с сердечником. Получены результаты экспериментально-теоретического моделирования на макете ограничителя тока с криогенным охлаждением магнитной системы, которые подтверждают повышение энергоэффективности разработанного конструктивно-технического решения

Ключевые слова: ограничитель тока, высокотемпературный сверхпроводник, экран, обмотка, магнитопровод, короткое замыкание, потери мощности

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1. Introduction

Modern advances in the field of power engineering are characterized by the emergence of the super-high classes of voltages, utilization of large unit capacities, and creation of energy complexes of high power. These factors sharpen an actual problem of limiting short circuit currents, which are among the defining parameters when choosing equipment for substations and power transmission lines.

For this purpose, electric units and control methods for short circuit currents are effectively used, such as vacuum breakers, fast acting switches, melting safety fuses, reactors that use high impedance transformers, but they all have certain shortcomings.

A task of using the phenomenon of superconductivity in the process of technical re-equipment of power engineering requires detailed analysis, including in the protection power equipment, in particular short-circuit current limiters (SCCL). The benefits of using superconducting SCCL are as follows:

– high performance speed;

– excessively low resistance compared with traditional current limiting reactors in the normal mode;

– reduced losses of power;

– a decrease in weight, size and cost of the power equipment;

– a possibility of using automatic circuit breakers with lower current interrupting characteristics and of applying more efficient schemes of electric power line performance.

In addition, resistance of a limiter increases almost without inertia in case of short circuit and limits the current to the required magnitude.

An inclusion of SCCL into certain components of a power system along with protection devices will ensure efficiency of the protection schemes performance, prolong the life time of work of the devices and will create conditions for a gradual replacement by modern equipment.

Designing superconducting fast performing energy efficient short-circuit current limiters is a very important and promising task, which focuses on the implementation of technology of high-temperature superconductors in electrical power engineering and protection of electrical networks and electric equipment from accidental short circuit currents.

2. Literature review and problem statement

Active development of superconducting current limiters (SCL) with high temperature superconducting (HTSC)

elements started simultaneously with the advent of HTSC. It is associated with the improved properties of HTSC, a possibility to obtain superconductivity when cooling with liquid nitrogen (at temperature 77 K) [1].

By the design features, one can select and examine two basic schemes of SCL: resistive (Fig. 1) and inductive [2]. They form the base for the most of other proposed set-ups that must meet the same requirements.

Resistive design of SCL is based on the nonlinearity of resistance of a superconductor. SCCL contains a superconducting (SC) element that is connected in series to the circle, which is protected. Structurally, these elements can be fabricated as a set of thin PE films or massive elements connected in parallel and in series.
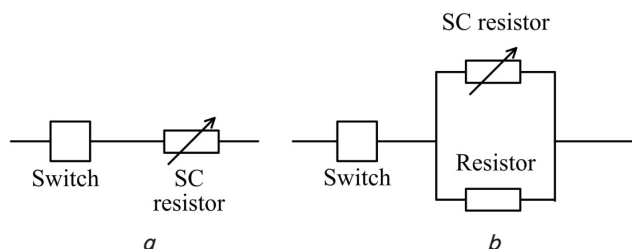

Fig. 1. Resistive SCL: *a* — serial type; *b* — shunt type

Under the normal mode of operation of the protected circle, the amplitude of nominal current is lower than the critical current of the SC element. An SC element is in a superconducting state with zero resistance. In an emergency mode, the ShC current in the circle grows and causes transition of the SC element to resistive state. Active resistance of the SC element increases and full resistance limits the ShC current. The principle of shunt type is similar to sequential but in this case, the resistor or winding is switched in parallel to a superconductor. Despite its simplicity, resistive design of current limiter has a number of shortcomings similar for different types of schemes.

Main schemes of HTSC current limiters of resistive type:

1. Nexans (Germany) CULR-10 (10 kV; 0.6 kA) [3], CULT-110 (63.5 kV; 1.8 kA) [4], which are based on the use of HTSC elements. Their disadvantage is considered to be the possibility of occurrence of thermal domains due to heterogeneity of transition of the superconductor. This may lead to the destruction of the SC elements.

2. Siemens (13 kV; 0.3 kA) [5], which are based on the use of thin-film HTSC elements. In an emergency mode, when short circuit current passes through the SC elements, there is a significant amount of heat released, which leads to bubble boiling of nitrogen and to even more extensive heating; ensuring low ohm reliable contacts; inertial performance up to 10 ms.

3. SuperPower (USA), Matrix (138 kV; 0.4 kA) requires a significant amount of serial-parallel connected SC elements, which increases the cost [6]. The shortcomings of this design also include a necessity to ensure alignment of critical parameters of all SC elements; increasing the dimensions compared to resistive design.

Inductive design of SC current limiter is rather promising. Inductive SCL uses nonlinearity of volt-ampere characteristic of superconductor, but the introduction in the circle of inductive resistance. Thus, one cannot expect significant heat release in the mode of current limitation. This type

of design may be examined on the example of replacement scheme of transformer with SC resistor as a load of the secondary winding (Fig. 2).
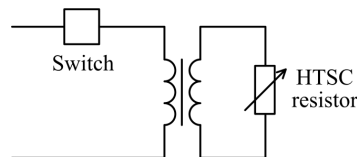

Fig. 2. Inductive SCL

Limiting short-circuit current in SCL of inductive type is achieved by a sharp rise in its inductive resistance. This can be achieved by different methods: when the secondary winding, which screens, is trapped on superconducting element; when as the secondary winding they use SC screen that screens the core from the penetration of magnetic flux; by changing a degree of saturation of magnetic circuit [7].

At present, the following basic schemes of inductive type of HTSC current limiter are under design:

1. ABB (Switzerland) screened (10.5 kV; 70 A), where the radii of coils and magnetic core increase in proportion to nominal voltage, that is, weight and size parameters and energy expenses [8, 9].

2. General Atomics with electronic control system (15 kV; 80 A) [10]. The shortcomings of the design include extremely high price and low reliability of performance. In addition, complexity of design of electronic system and the need for additional power supply source and control unit.

3. With saturated magnetic circuit Zenergy Power (138 kV; 1.3 kA) [11]; InnoST (35 kV; 0.2 kA) [12]. Current limiter with saturated magnetic circuit is a non-linear device that can degrade the quality of network voltage even under nominal mode of operation. In addition, the main HTSC winding requires an additional power source.

The main disadvantage inherent to inductive current limiters is dimensions and weight. It is also necessary to conduct a theoretical analysis of power losses to develop such an SCL.

Thus, the problem of improvement of constructive solution on inductive current limiter consists in the fact that the radii of coils and magnetic core increase in proportion to nominal voltage, that is, weight and size parameters and energy expenses.

3. The aim and tasks of the study

The studies we conducted set the aim to develop scheme and theoretical solutions to improve operational-technical parameters of inductive limiter of short circuit current with superconducting elements.

To achieve the set aim, the following tasks were to be solved:

– to design a technical solution to improve reliability and efficiency of emergency current limit;

– to run an analysis of efficiency and determine the effect of a full cryogenic cooling of magnetic system of current limiter on power losses;

– to conduct a simulation on the experimental model to determine the influence of cryogenic environment on power losses in the core of current limiter.

4. Development of the concept of superconducting current limiter

Using 2G HTSC wires makes it possible to make HTSC winding and, accordingly, introduce them into design of a current limiter of inductive type. That is why we propose a design of HTSC current limiter that uses superconductive elements using the latest achievements in this field. In the given device, the activation does not lead to significant heat release, which does not cause overheating of the superconducting element [13].

The developed design of short circuit current limiter (Fig. 3) contains a stacked magnetic circuit 1, the middle rod of which holds HTSC screen 2; outside, basic HTSC winding 3 is designed to turn on in the phase of electricity network through current inputs 4 to protect against emergency current with full placement in cryostat 5, which is filled with liquid nitrogen [14].
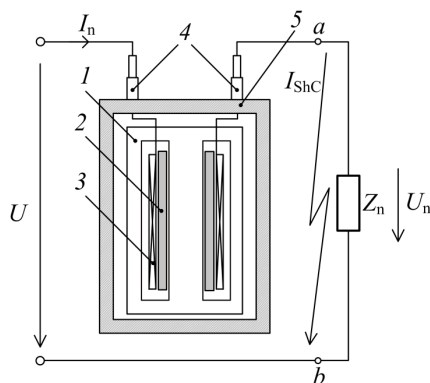

Fig. 3. Schematic representation of HTSC SCCL with screened core and its switching scheme

Under the normal mode of network operation, basic winding 3 of the limiter lets through nominal current of the load ($I=I_n$). HTSC screen 2 is in superconducting state, that is, it has diamagnetic properties and does not let through magnetic flux to the middle rod of the core. Winding 3 is made of HTSC wire, which has no resistance under superconducting condition. HTSC screen does not let through magnetic flux of coil 3 to the core of magnetic circuit 1. Thus HTSC winding 3 has low inductance (Fig. 4).
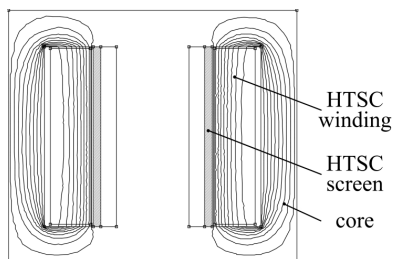

Fig. 4. Distribution of magnetic field in the SCCL screen in superconducting state

Inductance at superconducting state of the HTSC screen:

$$L_{SC} = \frac{\Psi}{i} = \mu_0 w^2 \frac{2\pi r_m b_{win}}{3 h_{win}}, \qquad (1)$$

where w is the number of turns of winding; r_m is the mean radius of winding; h_{win} is the width of section of winding;

h_{win} is the height of section of winding; μ_0 is the magnetic constant.
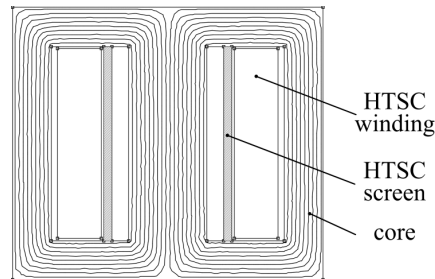

Fig. 5. Distribution of magnetic field screen in SCCL superconductivity of the screen is lost

In case of short-circuit of the load, or the line between a and b (Fig. 3), current increases ($I=I_{cr}>I_n$) with an increase in magnetic field intensity on the surface of HTSC screen 2 from the basic HTSC winding 3. As soon as the magnetic field exceeds critical value B_{cr} for HTSC screen 2, it will lose its superconductivity and diamagnetism. Magnetic flow will enter the middle rod of magnetic circuit 1 and concentrate in the core (Fig. 5).

At the loss of superconducting state by HTSC screen magnetic flows of scattering can be disregarded and inductance may be expressed:

$$L_{cr} = \frac{B_{st}\left(H_{cr}\right)\pi r_{st}^2 w}{k_{Iscr} \cdot i_n}, \qquad (2)$$

where r_{st} is the radius of cross-section of the core; B_{st} is the induction of magnetic flux of material of core $B_{st}(H_{cr})$; $H_{cr}=B_{cr}/\mu_0$ is the critical tension at the loss of superconductivity of HTSC screen; k_{Isc} is the coefficient of exceeding nominal current, at which superconductivity of HTSC screen is lost.

Due to nonlinearity of magnetic properties of the core, there is a possibility of substantial reduction in short circuit current I_{cr}, but it does not affect the HTSC screen since the magnetic flow entered the middle rod. The inductance of basic winding 3 increases accordingly, as well as its inductive resistance. Thus, the resistance of HTSC current limiter will increase, which in turn limits the current of short circuit [15].

An advantage of the proposed device is that the basic winding is made of HTSC wire and is placed in cryostat, which ensures the reduction in thermal losses under normal mode, dimensions of the basic winding. The device has reduced power losses under normal mode.

5. Analysis of energy efficiency of superconducting current limiter

Let us consider the designed variant with capacity $S_n=2,4$ MVA (Table 1) [16]. The losses for cooling are associated with external heat tides:
– by current inputs;
– through the walls of cryostat.
Internal heat tides:
– hysteretic losses from alternating current in the conductors of HTSC winding;
– losses of power in the core.

Table 1

Parameters of superconducting current limiter of inductive type

Parameter	Magnitude
Throughput capacity S_n, MV·A	2,4
Core's cross-section radius r_{st}, m	0,105
Width of magnetic circuit A, m	0,471
Height of window of magnetic circuit h, m	0,84
Height of superconducting screen h_{scr}, m	0,82
Number of turns of superconducting winding, w	367

Thus, thermal output has the following components:

$$P_{term} = P_{cor} + P_{ext} + P_{hys} + 2P_{ci}, \qquad (3)$$

where P_{cor} are the magnetic losses in the core of magnetic circuit; P_{ext} are the external heat tides through the walls of cryostat; P_{hys} are the hysteretic losses in the wires of SC winding at re-magnetization; P_{ci} is the tide of heat through a current input.

Magnetic losses in the magnetic circuit of current limiter when operating under nominal mode are determined by the induction in core, which is at the level of B_{cor}=0,01 T. Specific losses, for example, in electro-technical sheet steel St. 1511 of thickness 0.5 mm at B=1 T are p_{spec}=1,55 W/kg [17].

The volume of steel of magnetic circuit for nominal regime

$$V_{cor} = 2\pi \cdot r_{st}^2 \left(\frac{1}{2} h + A \right) =$$
$$= 2\pi \cdot 0,105^2 \left(\frac{1}{2} 0,84 + 0,471 \right) = 0,0617 \ m^3. \qquad (4)$$

General magnetic losses in the core of current limiter will be [18]:

$$P_{cor} = p_{spec} \gamma_{st} V_{cor} B_{cor}^n =$$
$$= 1,55 \cdot 7550 \cdot 0,0617 \cdot 0,01^2 \approx 0,1 \ W, \qquad (5)$$

where γ_{st} is the specific density of electro-technical steels (7550 kg/m³ St. 1511–1514).

To reduce magnetic losses, it is possible to use a magnetic circuit made of dispersed iron with negative temperature coefficient of resistance [19].

Let us consider a heat tide through a current input of length l with cross-section s, the external temperature of which is T_1=0, and at the end T_2 (x=l) is the temperature of liquid nitrogen.

Differential equation of thermal conductivity for current input [20]

$$\frac{d^2 T}{dx^2} + \frac{\rho I^2}{\lambda s^2} = 0, \qquad (6)$$

where I is the current passing through a current input; ρ is the specific resistance of material of the current input; λ is the coefficient of thermal conductivity of material of the current input.

A solution of differential equation (6) takes the following general form:

$$T = -\frac{\rho I^2}{\lambda s^2} \frac{x^2}{2} + A_1 x + A_2, \qquad (7)$$

where A_1 and A_2 are the integration constants that are determined from boundary conditions (at x=0, T=T_1, at x=l, T=T_2):

$$T_1 = A_2; \quad T_2 = -\frac{\rho I^2}{\lambda s^2} \frac{l^2}{2} + A_1 l + T_1,$$

wherefrom

$$A_1 = \frac{1}{l} \left[\frac{\rho I^2}{\lambda s^2} \frac{l^2}{2} - (T_1 - T_2) \right].$$

Thus, at the accepted boundary conditions, the temperature of current input

$$T = -\frac{\rho I^2}{\lambda s^2} \frac{x^2}{2} + \left[\frac{\rho I^2}{\lambda s^2} \frac{l^2}{2} - (T_1 - T_2) \right] \frac{x}{l} + T_1, \qquad (8)$$

while the heat tide through a current input to a cryostat will be as follows

$$P_{ci} = -\lambda s \frac{dT}{dx} \bigg|_{x=l} =$$
$$= \lambda s \left(\frac{\rho I^2}{2\lambda s^2} l + \frac{T_1 - T_2}{l} \right) = \frac{\rho I^2}{2} \beta + \lambda \frac{T_1 - T_2}{\beta}, \qquad (9)$$

where β=l/s is the parameter that describes the geometry of current input. The tide of heat to the cryostat depends on parameter β whose minimum value satisfies condition:

$$\frac{dP_{cв}}{d\beta} = 0,$$

which gives

$$\frac{\rho I^2}{2} - \lambda \frac{T_1 - T_2}{\beta^2} = 0.$$

From here $P_{ci \ min}$ satisfies

$$\beta_{opt} = \frac{l}{s} = \sqrt{\frac{2\lambda (T_1 - T_2)}{\rho I^2}} \qquad (10)$$

minimum tide of heat per one current input in this case will be as follows

$$P_{ci min} = I \sqrt{2\lambda \rho (T_1 - T_2)}. \qquad (11)$$

For one copper current input it equals (in the range of temperatures T_1=290 K, T_2=80 K)

$$P_{ci min} = k_{ic} I,$$

where

$$k_{ic} = 0,04 \ W/A. \qquad (12)$$

To reduce the tide of heat, it is possible to use the current inputs that are blown through with cold nitrogen, which is released; it allows obtaining the tide of heat through them at the level of 1.2–1.3 mW/A. [21, 22]. Thus, the tide of heat to two current inputs will make up approximately 1 W.

For the manufacture of HTSC winding, it is possible to use, for example, a tape superconductor of the 2G type YBCO (SJTU), experimental specific losses in which at alternating current when f=50 Hz are given in Fig. 6 [23].
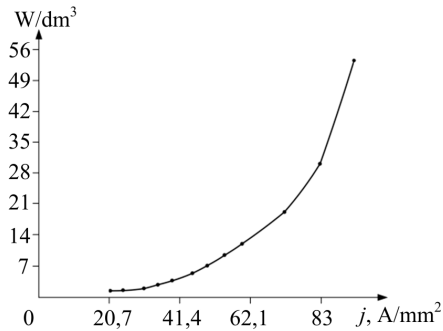

Fig. 6. Power losses in the HTSC wire at 77 K, f=50 Hz

A volume of the HTSC wire in the coil is

$$V_{SC} = 2\pi r_{win} w a_{wr} b_{wr},\qquad(13)$$

where r_{win} is the mean radius of winding; a_{wr} is the width of the HTSC wire; b_{wr} is the thickness of the HTSC wire.

At the dimensions of superconducting wire 15×0,5 mm^2, the density of current in it under nominal mode will compose j=55 A/mm^2, and the volume will be 2.05 dm^3. Accordingly, general losses in the HTSC winding will be at the level of 14.4 W.

The peculiarities of the HTSC SCCL performance are related to the necessity of cooling of the temperature of liquid nitrogen, which requires the use of a cryostat.

Let us consider a non-metallic cryostat, its casing has double walls from material of the electrical textolite type (Δ_1=15 mm; λ_1=0,2 W/m °C). Between the double walls is vacuum space (p=10^{-2} mmHg) in which, to reduce the tides of heat, there is a layered vacuum insulation (Δ_2=20 mm; λ_2=0,001 W/m °C) [24].

Equivalent coefficient of thermal conductivity of such a structure

$$\lambda_e = \frac{\lambda_1\lambda_2(2\Delta_1 + \Delta_2)}{2\Delta_1\Delta_2 + \Delta_2\lambda_2},\qquad(14)$$

and given the magnitudes of the first order of smallness

$$\lambda_e \approx \lambda_2 \frac{2\Delta_1 + \Delta_2}{\Delta_2} = 0,001\frac{2\cdot 15 + 20}{20} = 0,0025 \text{ W/m °C}.$$

Surface of cryostat F_{cryo}, through which heat passes:

$$F_{cryo} = \pi A\left(\frac{A}{2} + h + 2r_{st}\right).\qquad(15)$$

The tide of heat to the cryostat is

$$q_{st} = \lambda_e \frac{T_1 - T_2}{2\Delta_1 + \Delta_2}F_{cryo}.\qquad(16)$$

Thus, if a cryostat is made of non-conductive material (plastic) with layered-vacuum insulation, it is possible to get external tides of heat to the cryostat at the level up to q=10–15 W/m^2 [25].

In the designed structural scheme of the HTSC current limiter, the influence of scattering flows is minimal (Fig. 4). Thus, it is possible to use a metal cryostat, owing to which the tides of heat will be reduced (experimental heat flow density is q=2.62 W/m^2) [26].

Accordingly, the tide of heat through the surface of a metal cryostat will be

$$q_{st} = q\, F_{cryo} = 2,62\cdot 1,9 = 5 \text{ W}.$$

Thus, the total thermal power to release from a metal cryostat

$$P_{\Sigma term} = P_{cor} + P_{ext} + P_{hys} + 2P_{ci} = 0,1 + 5 + 14,4 + 1 = 20,5 \text{ W}.$$

In order to withdraw the heat from the cryostat and maintain in it the temperature of liquid nitrogen (to 77 K), it is necessary to use on cooling the power by an order of magnitude larger than the power of heat release (Table 2) [2].

Table 2

Power of refrigerator for heat withdrawal of 1 W

Temperature, K	200	150	100	77	30	4
Power, W	2	4	8	12	80	2000

Thus, the power that it is necessary to use is

$$P_{cool} = 12\, P_{\Sigma term} = 12\cdot 20,5 = 246 \text{ W}.$$

When cooling with liquid nitrogen, it will evaporate per one hour

$$Q = P_{\Sigma term}/r_n = 20,5/49 = 0,42 \text{ l/hours},\qquad(17)$$

where r_n is the heat of nitrogen vaporization.

Taking into account all types of efficiency, HTSC SCCL will be equal to

$$\eta_{cor} = \frac{S_n\cos\phi_n}{S_n\cos\phi_n + P_{cool}} = \frac{1385\cdot 10^3\cdot 0,97}{1385\cdot 10^3\cdot 0,97 + 246} = 0,99.\qquad(18)$$

The calculation was carried out without regard to the location of SCCL switching, which is why during ShC a part of voltage will remain in the electrical network, that is, the voltage at SCCL may reach (0,75–0,85) U_n. Accordingly, the dimensions may be reduced, and that is why, when using steel with larger induction saturation, the power losses may further decrease. The results of the HTSC SCCL parameters are presented in Table 3 compared with the traditional current limiting reactor RBA-6-400-3 [27].

Table 3

Comparative parameters of current limiters

Inductive type of current limiter	Power losses P, W	I_{ShC}	Weight, kg
HTSC screen and winding	~250	8·I_n[1]	562[2]
HTSC screen, copper winding (ABB)	~1000	11·I_n[1]	1300[2]
Current limiting copper reactor RBA-6-400-3	1700	33,3·I_n[1]	520

Notes: [1] is the multiplicity of value of the shock current of short circuit; [2] is the weight of magnetic circuit

Thus, the developed scheme of inductive current limiter with high-temperature superconducting HTSC screen and winding of the second generation of magnetic system, which is fully placed within a single cryostat will provide for the enhancement of operational indicators compared with the known analogues. In comparison with the closest equivalents – inductive superconducting current limiter by the firm ABB (Switzerland) and traditional reactor, we increased energy efficiency, improved weight and dimension indicator of magnetic circuit with superconducting analogue, improved the rate of limit of short circuit shock current (Table 3).

6. Simulation of power losses in the core of a current limiter

To experimentally determine magnetic power losses in the magnetic circuit of a current limiter, we used rectangular core with negative anchor (Fig. 7), on which a cryo-resistive winding is installed whose number of turns is w=1000. The core is made of sheet electro-technical steel St. 1512 of sheet thickness 0.5 mm and the fill factor of steel at k_i=0,93.

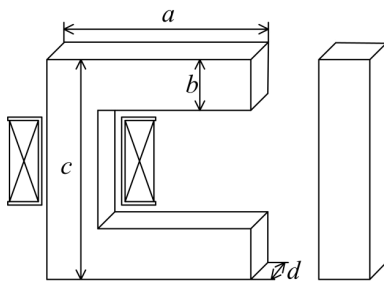Fig. 7. Rectangular core of SCCL: a — 12 cm; b — 4 cm; c — 16 cm; d — 1.5 cm

To reproduce actual working conditions of a high-temperature superconducting current limiter, the winding, which is made of copper, together with the core, is placed inside a cryostat and cooled with liquid nitrogen to temperature ~77 K.

Experimental electric circuit to conduct the research is mounted on a universal stand. Schematic representation of the electrical circuit for the measurements of the first stage is demonstrated in Fig. 8.
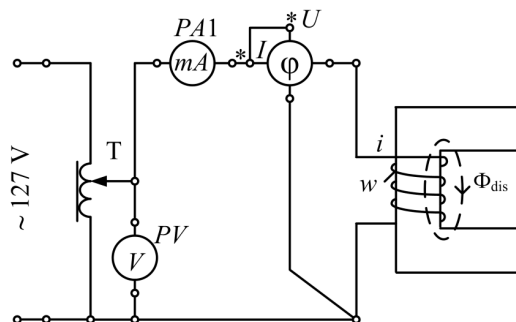
Fig. 8. Electrical circuit for the measurements of the first stage

The circuit power supply is fed from the AC source of voltage 127 V at frequency f=50 Hz. Voltage regulation is carried out by compensator T. Voltage measurement is conducted by the multimeter PV (DT-832), current measurement is performed by the milliammeter PA1 (ACT), measuring the angle of phase shift is done by the phase meter (D578).

Magnetic flow, generated by MMF of cryoresistive winding, corresponds by the magnitude to the nominal superconducting current limiter mode when magnetic induction of the flow in the core is B_{cor}~0,01 T. Thus, we determined voltage U≈2 V, appropriate to create the required level of magnetic induction in the core that feeds the winding at the first stage of the experiment.

Additional control calculations of magnetic field by the parameters for the selected magnetic circle were performed in the FEMM program. The results of calculation of magnetic field of the open-loop core are presented in Fig. 9.

The results of calculation of the magnetic circle by FEMM demonstrate that magnetic induction in the core is equal to B_{cor}=0,01 T and the winding voltage is equal to U=2 V.
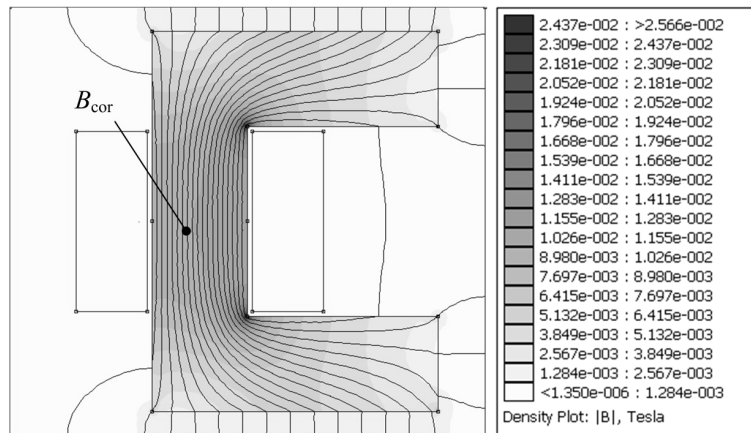
Fig. 9. Results of calculation of magnetic field

The measured current, voltage and angle of phase shift allow us to determine the power losses for the regime, which corresponds to standard work of a current limiter.

During the first stage of the experiment, measuring devices demonstrated the following results: voltage magnitude of the winding U=2 V, current in the winding I=2.5 mA, phase shift angle φ=68°. It was also defined by the method of ammeter (E514) and voltmeter (V–1500/5) that resistance of the winding cooled with nitrogen is R_{win}=1,25 Ohm.

Active power of the simulation corresponds to the total power losses in the winding and core

$$\Delta P = U \cdot I \cdot \cos\varphi = 2 \cdot 2,5 \cdot 10^{-3} \cdot \cos 68° = 1,87 \text{ mW}. \qquad (18)$$

Power losses in the winding

$$P_e = R \cdot I^2 = 1,25(2,5 \cdot 10^{-3})^2 = 7,8 \cdot 10^{-3} \text{ mW}. \qquad (19)$$

Power losses in the core

$$P_{cor} = \Delta P - P_e = 1,86 \text{ mW}. \qquad (20)$$

Accordingly, specific power losses with regard to the mass of the core will amount to 0.5 mW/kg, so under the nominal operating mode of a current limiter one may expect losses P_{cor}=0,17 W. Therefore, the obtained experimental results, if we take into account the reduction in resistance

of the steel core when cooled with liquid nitrogen, confirm previous calculations.

At the second stage of the experiment we will determine magnetic power losses in the core that will match the mode of short circuit. Let us assume that magnetic induction in the core of a current limiter is B_{cor}=1,5 T under the mode of current limit. Accordingly, in this case, the required voltage to power the winding of the examined magnetic circle is U≈200 V, which will create such magnetic induction in the core.

The experiment was conducted with magnetic circuit, closed by negative anchor, the current was measured by the ammeter PA2 (E514), voltage by the voltmeter (E545), power by the wattmeter (D5004) by scheme Fig. 10.
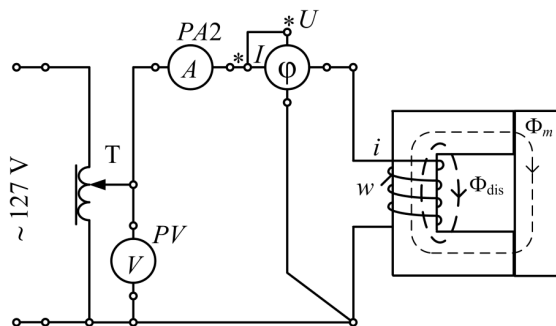

Fig. 10. Electric circuit for the measurements of the second stage

At the second stage of the experiment we obtained the following results: winding voltage magnitude U=200 V, current in the winding I=1.1 A, general power losses ΔP=17 W.

Accordingly, power losses in the winding

$$P_e=I^2 \cdot R=1,1^2 \cdot 1,25=1,5 \text{ W.}$$

Power losses in the core

$$P_{cor}=\Delta P - P_e=15,5 \text{ W.}$$

Power losses in the core given its mass will equal 3.29 W/kg. At the limitation of current, the losses in the core of a current limiter with throughput capacity S_H=2,4 MV·A (weight from Table 3) will reach P_{cor}=1,85 kW.

Thus, when limiting short circuit current, the evaporation of nitrogen due to magnetic losses in the core will be Q=P_{cor}/r_n=1850/2940=0,63 l/min, but this process is fairly short-term, so the evaporation of nitrogen is insignificant.

7. Discussion of results of research into analysis of the effect of cryogenic cooling of magnetic system on the energy efficiency of a current limiter

The results obtained during research indicate that under nominal operating mode, power losses in the magnetic circuit of inductive SCL approach zero. That is why the placement of inductive SCL with magnetic circuit to the cryostat significantly affects the reduction of power losses, dimensions of SCCL and improves conditions of its operation (Table 3). Further research would require a number of experimental studies at a semi-industrial prototype of inductive SCL. An improvement in the operating parameters

of inductive SCCL is possible to achieve through the use of electro-technical steel with larger induction saturation but it requires additional calculations.

Further implementation of SCL will be promoted by massive introduction of HTSC technologies and by increasing the volumes of sale of HTSC wires 2G [28]. Accordingly, the implementation of SCL will economically meet general standard requirements.

Thus, the ultimate cost of a high-temperature superconductor, as well as manufacturing technology and the peculiarities of operation of such SCCL, will require consequent research [29].

Improving the implementation of a high-temperature superconducting SCCL in electrical system is possible when using a HTSC cable of the power line in combination with the HTSC electric energy devices [30].

8. Conclusions

1. Placing a magnetic circuit of inductive screened current limiter with superconducting winding in the middle of a cryostat reduces magnetic fields of scattering. Thus, improved reliability is ensured by the use of a metal cryostat that improves electromagnetic compatibility. A current limiter provides for a rapid activation and limitation of emergency power due to a significant increase in inductive resistance. Using a superconducting winding in the emergency mode may provide for an introduction of active resistance to the circle, which also will contribute to limiting the current effectively.

2. It follows from the analysis of basic power losses in a current limiter, as well as analysis of the magnitude of tides of heat to a cryostat, that the effect of cryogenic cooling of a magnetic circuit on the power of heat release from a current limiter is insignificant and amounts to less than one percent.

3. We determined experimentally that in a magnetic circuit of a current limiter, placed in the cryostat filled with liquid nitrogen, the power losses are insignificant. Simulation results on the examined model agree with the performed calculations and confirm that placing the core of a current limiter in the middle of a cryostat practically has no any effect on the general power losses.

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Виконано аналіз втрат в вихідних параметрах сонячних елементів на основі телуриду кадмію, які зумовлені особливостями конструкції приладової структури і фотоелектричними процесами, які відбуваються в її об'ємі при поглинанні світла. Досліджено реалізовані підходи до підвищення коефіцієнта корисної дії фотоелемента на основі CdS/CdTe і їх результативність. Запропоновано шляхи підвищення ефективності таких плівкових сонячних елементів при удосконаленні способу отримання тильного контакту

Ключові слова: плівковий сонячний елемент, гетероструктура, телурид кадмію, вихідні параметри, тильний контакт

Выполнен анализ потерь в выходных параметрах солнечных элементов на основе теллурида кадмия, которые обусловлены особенностями конструкции приборной структуры и фотоэлектрическими процессами, происходящими в ее объеме при поглощении света. Исследованы реализованные подходы к повышению коэффициента полезного действия фотоэлемента на основе CdS/CdTe и их результативность. Предложены пути повышения эффективности таких пленочных солнечных элементов при усовершенствовании способа получения тыльного контакта

Ключевые слова: пленочный солнечный элемент, гетероструктура, теллурид кадмия, выходные параметры, тыльный контакт

INCREASING THE EFFICIENCY OF FILM SOLAR CELLS BASED ON CADMIUM TELLURIDE

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1. Introduction

Solvinga complex set of energy-ecological problems in Ukraine is impossible without a large-scale use of alternative energy sources. Solar power engineering according to many predictions is one of the most promising sectors of renewable power engineering.

The lowest cost of the generated electrical energy is demonstrated by film solar cells (further denoted SC) based on cadmium sulfide and telluride. In addition, SC based on cadmium sulfide and telluride possess high degradation durability, which enlarges the scope of their application.

Thus, the film SC based on CdS/CdTe are an alternative to traditional solar cells based on Si and GaAs. However, their large-scale industrial production is held back by the low value of performance efficiency of experimental models. Low value of efficiency, despite high technological efficiency of contemporary vacuum methods of obtaining the films of cadmium sulfide and telluride, is caused to a considerable degree by the physical-technological problems of formation of low-ohmic back contacts to the base layers of p-CdTe. Thus, the relevance of conducting given research is predetermined by the need for further development of physical-technological base for obtaining electrical back contacts to film SC based on CdS/CdTe.

2. Literature review and problem statement

Solar cells based on crystalline silicon and thin films are the most widely used commercial technologies in the field of