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ANALYSIS OF DESIGN FEATURES OF INDUCTIVE ELECTROMAGNETIC CURRENT LIMITER

The design circuits of an electromagnetic short-circuit current limiter of inductive type with movable armature and moving core are considered. A comparative analysis of the design features of the electromagnetic current limiter with copper or superconducting winding is carried out. The operation principle of the electromagnetic short-circuit current limiter of inductive type with copper or superconducting winding is considered. The peculiarities of operation modes of the electromagnetic short-circuit current limiter of inductive type with copper or superconducting winding are analyzed. Using results of the mathematical modeling of the magnetic system of the electromagnetic short-circuit current limiter by the Finite Element Method in the FEMM software environment, the character of the distribution of the magnetic flux density in the nominal mode and in the current limiting mode is determined, which allows to determine the parameters of the current limiter and design features. In accordance with the design features of the electromagnetic short-circuit current limiter of inductive type, the sequence of calculation of the basic parameters of the magnetic system, taking into account the voltage drop factor, is given. The basic equations of the electric equilibrium of the voltage drop of the electromagnetic short-circuit current limiter of inductive type for nominal mode and short-circuit conditions are given. The use of the design circuit of the electromagnetic short-circuit current limiter with superconducting winding can provide energy-saving in nominal mode. The use of high-temperature superconducting wire due to increased critical parameters will ensure preservation of the superconducting state of the winding in short-circuit mode.

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

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ANALIZ KONSTRUKTIVNYH OSOBLIVOSTEY INDUCTIVNOGO ELEKTROMAGNITNOGO OBERMEZUHACHA STRMU

Розглянуто конструктивні схеми електромагнітного обмежувача струму короткого замикання індуктивного типу з рухомим якорем та рухомим ярмом. Проведено порівняльний аналіз конструктивних особливостей електромагнітного обмежувача струму з мединою або надпровідною обмоткою. Розглянуто принцип дії електромагнітного обмежувача струму короткого замикання індуктивного типу з мединою або надпровідною обмоткою. Проаналізовано особливості режимів роботи електромагнітного обмежувача струму короткого замикання індуктивного типу з мединою або надпровідною обмоткою. За результатами математичного моделювання магнітної системи електромагнітного обмежувача струму короткого замикання індуктивного типу з мединою або надпровідною обмоткою, що дозволяє визначити параметри обмежувача струму та конструктивні особливості, відповідно до конструктивних особливостей електромагнітного обмежувача струму короткого замикання індуктивного типу наведено порядок розрахунку основних параметрів магнітної системи, що враховує коекфіцієнт спаду напруги. Наведені основні рівняння електричної рівноваги спаду напруги електромагнітного обмежувача струму короткого замикання індуктивного типу для номінального режиму та короткого замикання. Використання конструктивної схеми електромагнітного обмежувача струму короткого замикання з надпровідною обмоткою може забезпечити енергосбереження у номінальному режимі. Застосування високотемпературного надпровідного проводу завдяки підвищеним критичним параметрам забезпечить збереження надпровідного стану обмотки у режимі короткого замикання.

Ключові слова: обмежувач струму, коротке замикання, високотемпературний надпровідник, індуктивність, магнітне поле, магнітопровід.

Introduction. The technical progress in the field of electric power industry is characterized by an increase in the generation of electricity, which is the cause of the emergence of ultrahigh voltage classes, the development and creation of new energy complexes of high power. In turn, the need to improve the quality of electricity requires the use of control and protection electrical apparatus of the corresponding level in power transmission grids.

Increasing the power consumption in the power grids, in turn, causes emergency currents of short-circuit, which leads to the destruction of electrical equipment, and protection from this negative phenomenon is a very topical task. Thus, one of the defining parameters when selecting the equipment of substations and transmission lines is the protection of power transmission lines and consumers of electricity from short-circuit currents.

In addition, the reconstruction and re-equipment of existing power systems requires the use of effective means of protection against emergency modes, which is an important task.
Various traditional protection devices for electrical grids and electrical equipment against emergency currents such as fuses, circuit breakers, current limiting reactors and various current limiting devices are known. Improvement of the characteristics of short-circuit current limiters (SCCL) can be achieved through the use of superconducting windings [1].

The goal and task of the research. The goal of the paper is to carry out a comparative analysis of the design features of electromagnetic short-circuit current limiters with copper and superconducting windings.

The task of the work is to analyze the influence of the design features of the magnetic system on the operation of the electromagnetic short-circuit current limiter.

Inductive electromagnetic current limiter with copper winding. Consider the design circuit of an electromagnetic (EM) short-circuit current limiter. The design circuit contains a ferromagnetic core 1 with a moving armature 2 which is attracted by a spring 3, and a network winding 4, which is located on a middle rod, connected successively to the load \( Z_l \) in the electric circuit (Fig. 1).

![Figure 1 - Design circuit of the EM SCCL](image)

The operation principle is based on increase of inductive resistance of SCCL winding at occurrence of short-circuit current. Operation of the EM SCCL with moving armature 2 lies in the fact that under the nominal load current \( I_n \), the magnetic flux density \( B_{is} \) in the air gap \( \delta \) between the armature 2 held by the spring 3 and the core 1 is small, so the armature 2 is not attracted to the core (Fig. 2, a). At normal operation, the EM SCCL is connected in series with the load \( Z_L \), and through the winding 4 the load current \( I_L \) passes [2].

![Figure 2 - Magnetic system of the EM SCCL](image)

At short-circuits, the current \( I_{cs} \) for a short time increases dramatically, and the force of armature traction at this stage is proportional to the current in the square. Therefore, the armature is attracted to the core and closes it (Fig. 2, b). The inductance of the current limiter increases by an order, which leads, on the one hand, to a decrease in current, and on the other hand, due to the magnetic non-linearity of the material of the core, to an even greater attraction of the armature [2].

After switching off the voltage of the electrical grid to eliminate the short-circuit, the current limiter is de-energized and the armature returns to its original position. The presence of a mobile armature of the short-circuit current limiter is associated with such shortcomings as the inertia of the operation. But such technical solutions are widespread in electrical apparatus and can be improved.

For the effective use of the EM SCCL it is necessary to analyze the peculiarities of its operation, and to determine the criteria for choosing the main parameters. So, depending on the nature of the load, the voltage drop on the SCCL, which is determined by the coefficient \( k_v \), can be set in such a way that the voltage reduction on the load according to the voltage of the electrical grid is not more than 5% [3, 4].

If we take into account the fact that the voltage drop on the SCCL, both in normal operation mode and at the short circuit, EMF of the self-induction is balanced, it is possible to write:

\[
U_{cl} = k_v U_n = 2\pi f \omega B_k S_n, \quad (1)
\]

\[
U_n = 2\pi f \omega B_k S_n, \quad (2)
\]

where \( f \) is frequency of alternating current; \( w \) is the number of turns of the winding; \( B_k \) is the magnetic flux density in the gap between armature and core in normal operation mode; \( B_k \) is the magnetic flux density in the core when connecting the armature with the core; \( S_n \) is the cross-section of the core; \( k_v \) is the coefficient of expansion of the magnetic flux in the gap between the armature and the core.

Accordingly, the number of turns of the winding \( w \):

\[
w = \frac{k_v B_k}{\mu_0 k_v \delta}, \quad (3)
\]

where \( \delta \) is the air gap between the armature and the core; \( \mu_0 \) is the magnetic constant.

From (1) we obtain the connection between magnetic flux densities: \( B_k = B_{is} (k_v / k_v) \). The value of the magnetic flux density \( B_k \) is selected on the part of the material's magnetization, and the coefficient \( k_v = 1.05...1.3 \) is determined by special calculations. The size of the cross-section of the middle rod of the core:

\[
S_{cs} = \frac{U_n}{\omega w B_k}, \quad (4)
\]

where \( \omega = 2\pi f \) is angular frequency.

From (4), by substitution of the number of turns from (3), we obtain the dependence of \( S_{cs} \) on \( S_n \) – the full load power:

\[
S_{cs} = \frac{\mu_0 k_v S_n}{\omega k_v B_k \delta}. \quad (5)
\]

Inductive electromagnetic current limiter with superconducting winding. One of the newest trends in power engineering is the use of high-temperature superconductors (HTSC) at a nitrogen temperature level (~ 77 K), unlike low-temperature superconductors (~ 4.2 K). The development of superconducting short-circuit current limiters is based on the use of physical properties of high-temperature superconductors [1].

A superconducting electromagnetic short-circuit current limiter is connected to a part of the electric grid for...
emergency currents protection. Such a device has a near-zero resistance in nominal mode unlike traditional current limiters. The principle of the operation of superconducting current limiter is based on the loss of the superconductivity by the conductive element during the flow of short-circuit current [5].

The use of current limiters with superconductivity can provide the extension of the life of the switching devices, creating conditions for its gradual replacement by modern equipment, as well as energy saving. But the introduction of the electromagnetic current limiters with superconducting winding requires analysis. Consider the design circuit of an electromagnetic superconducting short-circuit current limiter (Fig. 3) [6].

The middle rod of the ferromagnetic core 1 and the moving armature 2, which is held by the spring 3, covers the cryostat 5 with the HTSC winding 4. The current leads 6 connect the HTSC winding 4 to the electrical grid.

The HTSC winding is cooled by liquid nitrogen, which is fed to the cryostat, where it evaporates and outwards. The consumption of liquid nitrogen is determined by the flow of heat to the cryostat through its wall, along the current leads, and also (when operating on alternating current) by hysteresis losses in the HTSC winding. The HTSC winding of the current limiter is connected in series with the HTSC winding and, accordingly, of the cryostat.

As the numerical analysis shows, the increase of $B_c$ and $\delta$ makes sense to certain limits: magnetic flux density $B_c$ should not leave the saturation region of the magnetization curve (1.4…1.5 T); the air gap $\delta$ must correspond to the dimensionless parameter $\delta/a = 0.3…0.4$.

Figure 5 shows the design circuit of a short-circuit current limiter, which represents the general view of the device for connection to the electrical grid phase. The main winding is made of high-temperature superconductor of the second generation, and the cryostat in turn is filled with a coolant, in this case, nitrogen [8].

The middle rod of the ferromagnetic core 1 and the moving armature 2, fixed to the spring 3, covers the cryostat 5 with the HTSC winding 4. The current leads 6 connect the HTSC winding 4 to the electrical grid.

The advantage of the design circuit is that the winding

\begin{equation}
\mu_0 H_0 = \frac{B_0}{\delta}
\end{equation}

where $\mu_0$ is the magnetic constant; $H$ is the magnetic field strength; $I_n$ is the nominal current; $B_0$ is the magnetic flux density in the air gap; $\delta$ is the air gap between the armature and the core.

Thanks to the use of HTSC winding of the second generation wire, it is possible to reduce the energy consumption, which exceeds the parameters of the previous ones and has higher critical current density [10].

The difference of the magnetic system from the previous design circuit is due to the increase in the mass of the moving armature.

The advantage of the design circuit is that the winding
retains the superconducting state and does not transit to a normal resistive state, which ensures re-activation. Device power losses in normal mode are practically absent. The losses for cooling of the inductive electromagnetic superconducting current limiter with the cryostat are associated with external heat fluxes [11, 12].

Conclusions. With the increase of the air gap $\delta$ in normal operation mode, the inductive resistance decreases in nominal operating mode, at short-circuit the resistance increases by an order of magnitude.

In all design circuits, the volume and weight of the moving armature of the current limiter are proportional to $S_0$. The time of the actuation of the current limiter depends on the weight of the armature, this time will be smaller, the smaller will be $S_0$.

At given power, a decrease in the cross-section of the core $S_0$ is affected by the increase in the magnetic flux density $B$ in the closed core of the current limiter.

References (transliterated)
1. Dan'ko V.G. Vykoriystannya vysokotemperaturnoi nadprovidnosti v elektroenergetichnomu obладнанні [Use of high-temperature superconductivity in electric power equipment]: monograph. V. G. Dan'ko, I. S. Polyanska, E. V. Goncharov; edited by V. G. Dan'ko. – Kharkiv: NTU “KhPI”. 2011. – 248 p.

2. Dan'ko V.G., Goncharov E.V. The electromagnetic inductive short-circuit current limiter. Inżynieria i technologia. Nowoczesne badania podstawowe i stosowane. Warszawa. – 2016. – P. 4–45.

3. Dan'ko V.G., Goncharov E.V. Nadprovidny`j obmezhuvach strumu korotkogo zamy`kannya z ru`xomy`m yakorem. [Superconducting short-circuit current limiter with moving anchor]. Information technol ogy, science, engineering, technology, education, health: IX Int. sci. Practical Conf. (microCAD-2011), 01-03 June – Kharkiv: NTU “KhPI”. – 2011. – P. 147.

4. Dan'ko V.G., Goncharov E.V. Obmezhuvach strumu korotkogo zamy`kannya z ru`xomy`m yakorem i nadprovidnoyu obmotkoyu [Short-circuit current limiter with moving anchor and superconducting winding]. Information technology, science, engineering, technology, education, health: IX Int. sci. Practical Conf. (microCAD-2012), 15-17 May – Kharkiv: NTU “KhPI”. – 2012. – P. 156.

5. Dan'ko V.G., Goncharov E.V. Obmezhuvach strumu korotkogo zamy`kannya z ru`xomy`m yakorem i nadprovidnoyu obmotkoyu [Short-circuit current limiter with moving anchor and superconducting winding]. Information technology, science, engineering, technology, education, health: IX Int. sci. Practical Conf. (microCAD-2011), 01-03 June – Kharkiv: NTU “KhPI”. – 2011. – P. 147.

6. Dan’ko V.G., Goncharov E.V. Synthesis aspects of cryogenic high-temperature superconducting shielding inductive short-circuit current limiter / V.G. Dan'ko, E.V. Goncharov // Вісник НТУ “ХПІ”. – Київ: НТУ “ХПІ”. – 2017. – № 34(1256). – С. 9–13.

7. Dan'ko V.G. Synthesis aspects of cryogenic high-temperature superconducting shielding inductive short-circuit current limiter / V.G. Dan'ko, E.V. Goncharov // Вісник НТУ “ХПІ”. – Київ: НТУ “ХПІ”. – 2016. – № 32(1204). – С. 3–7.