Superconducting fault current limiter with fast vacuum commutation modulus.

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Abstract. A new approach to a problem of creation of a resistive version of superconducting fault current limiters (FCL) on the basis of HTS materials has been considered. According to this approach, a scheme of FCL is added by a commutation modulus which contains a fast vacuum interrupter. This interrupter allows one to switch off the transport current as soon as 5 ms after transition of the HTS element to the normal state. The proposed scheme allows one to restrict more than an order in value a necessary operation time of FCL in a regime of a current limitation. As a result, a time of recovering the superconducting state can be significantly reduced that allows FCL to operate in automatic iterative regime. The considering device can operate not only in high voltage ac transmission lines but also in dc electrical networks. A numerical simulation of transit processes in a proposed scheme of FCL has been performed for different regimes and its features are analyzed with respect to other schemes of FCL. An experimental study of test mock-up commutation elements of FCL has been performed. This study demonstrates an efficiency of the proposed scheme. A test of a FCL model with the limiting current up to 15 kA has been realized.

1. Introduction

The issues of power supply reliability and protection of costly electrical equipment from damage due to short-circuits in electric systems become more vital as these systems become more powerful. Mechanical and thermal strains (proportional to the square of current) occurring in the system due to short circuits make engineers design all the components of the system with much greater tolerances, which causes a significant price boost of electrical equipment.

One of the solutions to this problem is the use of different current-limiting devices. The issue of current-limiter characteristics improvement is one of the challenges in power grids of any voltage class, as it has always been.

Designing of short-circuit current-limiters based on high-temperature superconductors (HTSC) is one of the most promising ways of electrical equipment protection [1, 2].

The resistive current-limiter on the basis of second generation HTSC appears to be one of the most promising technologies among the other current-limiters in terms of size and price. It limits current due to high nonlinearity of current-voltage characteristic in the process of transition from superconductivity to normal state.

Economic expediency of resistor-type current-limiters designing is specified by the cost of HTSC-coil and cryostat, which is proportional to the volume of superconductor. The minimum volume of HTSC-coil under the condition of its adiabatic heating is

\[ V \sim Uldt/C_p\Delta T \]

(1)

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is mainly specified by the network voltage $U$, amplitude of current $I$, thermal capacity $C_r$ in the normal state, duration of current-limitation mode $dt$ and the admissible temperature of HTSC-coil heating $\Delta T$.

Switchgear is supposed to provide automatic reclosing (ARC) for reliable electric power supply. ARC mode stands for reclosing of the network section where short circuit took place as fast as 0.3 seconds after it was switched off.

To provide the automatic reclosing mode, HTSC coil must regain its superconducting mode in a period faster than 0.3 seconds. The heating temperature of HTSC coil during current limitation can be decreased by increasing of the weight of HTSC-wire and shortening of current-limiting mode duration. Considering the high price of HTSC-wire ranging from $60$ to $100$ per a meter the way of weight increasing is not an option. The only alternative is to decrease the duration of current-limiting mode $dt$, which is determined by the total shutdown time of the network circuit-breakers. The total shutdown time of modern network circuit-breakers is approximately 3-5 cycles. These circuit-breakers are designed to cut off short-circuit currents as high as tens of kA.

Duration of current-limitation mode $dt$ can be reduced to half cycle if the HTSC element limiting short-circuit current to an acceptable value (less than 10 kA) is connected in series with a high speed vacuum circuit-breaker [3].

2. Basic circuit diagram of fault current limiter with vacuum commutation modulus.

The present paper outlines the circuit of the superconducting resistive current-limiting device with the use of high speed vacuum circuit-breaker and triggered vacuum switch with the purpose to reduce the duration of the current-limiting operation ($dt$). Such a diagram allows to limit and cut off short-circuit currents in the AC and DC networks. The basic circuit diagram is shown on figure 1.

![Figure 1. The basic circuit diagram of the superconducting current limiter.](image)

The current limiter features an HTSC resistive coil $R_2$, capacitor $C$, linear resistor $Z$ and high-speed vacuum circuit-breaker $CB$. To decrease the time it influences HTSC-coil $R_1$ the time of circuit-breaker $CB$ actuation shouldn’t exceed 5 ms.

Non-linear resistor $R_1$ is aimed at limiting switching overloads occurring at the moment of current cut-off with the circuit-breaker $CB$ and power absorption, accumulated in the inductance of the external circuit $L_1$. Electric circuit consisting of capacitor $C$, inductance $L_2$ and triggered vacuum switch TVS creates countercurrent in the circuit of circuit-breaker $CB$. The following equations must be true for current cut-off in circuit-breaker $CB$ and triggered vacuum switch TVS.
Capacitor $C$ is charged by resistance $Z$ after transition of the HTSC into the normal state. After the actuation of TVS alternating current with the frequency $\omega_2 \approx \frac{2\pi}{\sqrt{L_2C}}$ arises in $L_2C$ circuit. This current provides zero-crossing of current in the circuit-breaker $CB$ in condition the equations 2 and 3 are true.

The current-limiting device operates as follows.

When the current rises up to the current setting $I_0$, a command is given to move apart the contacts of the circuit-breaker $CB$. Parameters of HTSC are precisely selected to transition it from superconducting operation into normal state just before (~1 ms before) the contacts of the circuit-breaker are moved apart.

After the superconductor transitions to normal state the capacitor $C$ is charged up to the voltage $U_c \approx IR_2$. At the moment when the gap between the contacts is at maximum, a command is given to turn on the TVS. After the TVS is on, the current in $CB$ goes rapidly to zero until the current is finally off. Provided the conditions 2 and 4 are observed, an alternating current with frequency $\omega_1 \approx \frac{2\pi}{\sqrt{(L_1+L_2)C}}$ flows through the TVS and it is cut off when the current crosses zero for the first time. The energy accumulated in the inductance of the external circuit $L_1$ is absorbed by non-linear resistance $R_1$ and the full current rapidly drops to zero. After the HTSC $R_2$ returns to the superconducting state, current-limiting device for short-circuit is ready for work again.

As an example, a short-circuit current limiting process in the DC circuit was calculated. We have reviewed the electric circuit shown on figure 1. The calculation was made under the following conditions: rated voltage 4kV, inductance $L_1 = 2$ mH, capacitance of the capacitor $C=100$ $\mu$F, inductance $L_2 = 40$ $\mu$H, resistance $Z=10$ Ohm, HTSC resistance $R_2=1$ Ohm. The contacts of the circuit-breaker $CB$ are moved apart 3 ms after the setting current is reached. The superconductor transitions to normal state at $I=8$ kA. The level of voltage limitation in non-linear resistance is 9 kV. Figure 2 shows the currents in the circuit-breaker $CB$ (curve 1), $R_2$ (curve 2) and TVS (curve 3).

![Figure 2](image_url)
Figure 3. Diagrams of currents in current-limiter: 1-current of the inductance of external circuit $L_1$, 2-current of non-linear resistance $Z$, 3-current of capacitor $C$.

Figure 3 shows current changes in the inductance of external circuit $L_1$ (curve 1), HTSC voltage $R_2$ (curve 2) and capacitor voltage $C$ (curve 3). Figure 4 illustrates the change in voltage of the circuit-breaker $CB$ (curve 1), HTSC $R_2$ (curve 2) and capacitor $C$ (curve 3). The calculated diagrams of current and voltage show that circuit-breaker $CB$ is capable of disconnecting current 1 ms after the superconductor transitions to the normal state, after which the current in HTSC $R_2$ goes down to zero within 2 seconds.

Figure 4. Diagrams of voltage in current-limiter: 1- voltage of the circuit-breaker $CB$, 2- voltage of HTSC $R_2$, 3- voltage of capacitor $C$.

Thus, according to (1), the minimal volume of HTSC in the diagram of the switching superconducting current-limiting device for short-circuit currents can be significantly (by several times) reduced in comparison with other known superconducting current-limiting devices. This allows to reduce the cost of the superconducting current-limiting device.

3. Testing of the basic circuit diagram of the current limiter

Electric diagram of the experiment is shown on figure 5 HTSC-coil was simulated with a $R_1$ resistance connected in parallel with the vacuum interrupter $Q_3$ driven by electromagnetic drive $Y_3$. Closed
position of the contacts of $Q_1$ modeled the superconducting state of HTSC whereas the open contacts simulated the normal state of HTSC with resistance $R_1$. As $Q_1$ we used vacuum interrupter (VI) with a transverse axially symmetric magnetic field. Such a vacuum interrupter is capable of disconnecting direct current up to 300 A at voltage up to 10 kV [4].

The model of the current-limiting device consisted of HTSC-coil model ($R_1Q_3$) connected in parallel with the series-connected circuit of linear resistance $R_2=13$ Ohm and capacitor $C_1=5 \mu$F. The vacuum interrupter $Q_2$ with electromagnetic drive $Y_3$ was connected in-series to this circuit. For creation of a countercurrent impulse in circuit $Q_2$ the circuit containing capacitor $C_1$, inductance $L_1 = 2 \mu$H and a triggered vacuum switch TVS were used. In parallel $Q_2$ the nonlinear resistor $R_3$ limiting voltage at a level of 1.5 kV was connected.

![Figure 5. The test circuit.](image)

The experimental stand consisted from charging device $G$, the capacitor bank with capacity $C_0 = 10 \mu$F at maximum voltage 5 kV and inductance $L_0 = 6$ mH. The breadboard model of a HTSC current limiting device was connected to preliminary charged capacitor bank by means of vacuum contactor ($Q_1Y_1$). Before tests contacts in VI $Q_1$ were opened, and in VI $Q_2$ and $Q_3$ were closed. The maximum gap of contacts in all VI was $d = 4$ mm.

A current value was adjusted by change of charging voltage $U_0$. After charging of capacitor bank $S_0$, up to set up voltage $U_0$, control unit $CS$ gave out a command on closing contactor $Q_1Y_1$. After that with time delay the control pulse on opening contacts in $Q_2$ and $Q_3$ were applied. The triggering pulse on closing $TVS$ was applied approximately through 2-3 ms after transition of a current to resistance $R_1$.

During experiments a current in charging circuit was measured with a current sensor LT-100 working on the basis of Hall effect (106 A/V) and a current $I_l$ in the inductance $L_1$ was measured with Rogovsky coil with sensitivity 430 A/V. A voltage $U_1$ on resistor $R_1$ was measured with help of voltage divider with factor 1:217. A voltage $U_2$ on VI $Q_2$ was measured with voltage sensor based on Hall effect LV-100 with ration factor 1:200. Electric signals were registered with a digital oscillograph Tektronix TDS3000B with the subsequent computer-based processing.
The experimental testing of current-limiting model was carried out at voltage $U_0=500-600$ V. After the contacts of $Q_1$ were closed (without application of any control signals to $Q_2$ and $Q_3$) a sinusoidal current simulating short-circuit current flowed in the discharge circuit. This current had a period of 48.6 ms and an amplitude of the first half-wave equaling 550-670 A. When all the control impulses were applied the current-limiting device limited the current to 200-300 A with its subsequent switching-off in 2-3 ms. The delay for the control impulse applied to the drive of $Q_1$ was elaborately selected to provide for the current transition to resistance $R_1$ at current level $\sim$300A. The typical oscillograms of $I_0$ and $I_t$ currents and $U_0$ and $U_2$ voltages for $R_1=0.9$ Ohm and 1.9 Ohm are shown on figure 6 and figure 7 respectively. The oscillograms of currents and voltages match the results of numerical modeling.

![Figure 6](image1.png)

**Figure 6.** Oscillograms of currents $I_0$ (trace 2, 530 A/div., 2 ms/ div.), $I_t$ (trace 3, 860 A/ div., 2 ms/ div.) and voltages $U_1$ (trace 1, 434 V/ div., 2 ms/ div.), $U_2$ (trace 4, 1000 V/ div., 2 ms/ div.) at $R_1 = 0.9$ Ohm.

![Figure 7](image2.png)

**Figure 7.** Oscillograms of currents $I_0$ (trace 2, 530 A/div., 2 ms/ div.), $I_t$ (trace 3, 860 A/ div., 2 ms/ div.) and voltages $U_1$ (trace 1, 1085 V/ div., 2 ms/ div.), $U_2$ (trace 4, 1000 V/ div., 2 ms/ div.) at $R_1 = 1.9$ Ohm.

4. **Acknowledgments**

In course of experiments the short-circuit current-limitation circuit proved efficient both in AC and DC networks. That circuit provides for auto fine-tuning of the counter current impulse amount to the limiting current.

For testing of the current-limiting device we have designed a high speed vacuum circuit-breaker featuring 3 ms break-time, 3000 A rated current and breaking current up to 15 kA.

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5. References
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