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Analysis of Superconducting Fault Current Limiter 6 kV/0.14 kA

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The paper presents a 6 kV/0.14 kA superconducting fault current limiter. The 6 kV/0.14 kA superconducting fault current limiter is constructed so as to be cooled by a cryocooler in high vacuum cryostat. The operating temperature of the limiter can be changed, which results in a change in the operating current of the 6 kV/0.14 kA superconducting fault current limiter. An analysis of the effect of working temperature (from 40 K to 85 K) on the limiter's work has been presented.

topics: SFCL, superconducting fault current limiter, SF12100 superconducting tape

1. Introduction

The 6 kV/0.14 kA superconducting fault current limiter (SFCL) for medium voltage networks, for the construction of which the second generation high temperature superconductor (HTS) tape SF12100 has been used, is cooled using a cryocooler in high vacuum cryostat. The previous limiters built and tested by the authors [1–4], in which a cooling system in a liquid nitrogen bath was used, were at a constant operating temperature of 77.4 K (temperature before a short circuit). In this SFCL, the operating temperature can be changed. The parameters of the 6 kV/0.14 kA SFCL are calculated for the operating temperature of 77.4 K so its full name should be: "6 kV/0.14 kA (at 77.4 K)".

In the 6 kV/0.14 kA SFCL, the current flows through two parallel connected SF12100 tapes, each of 66 m long. The rated critical current of the SF12100 tape, provided by the manufacturer, is 300 A (at 77.4 K) [5–8]. This value is the minimum critical current value that each section (5 m) of SF12100 purchased tape must have. The 6 kV/0.14 kA SFCL operation has been analyzed at three temperatures: 72, 80 and 86 K, in which experimental short-circuit tests were carried out, and also at lower temperatures: 40, 50 and 60 K.

The numerical model used in the calculations is modeled on the previous numerical models described in [9, 10]. In the current numerical model of this limiter, the cooling system has been changed, from cooling in a liquid nitrogen bath to cooling using a cryocooler. In the numerical model, the short-circuit system has been reproduced from tests in the Switchgear and Controlgear Laboratory at the Institute of Electrical Engineering in Warsaw [11]. The current has been limited during the time of 0.08 s, then the short circuit has been disconnected by an external switch. In the numerical model, the short-circuit current flows from 0 s to 0.08 s. After that time, without the current, the limiter is subject to a cooling process for a time of 2.92 s.

2. Short-circuit current courses

The short-circuit current was limited in the first test at 72 K operating temperature from ≈ 80 kA (without the limiter) to a maximum of 1.9 kA. In the second short-circuit test, which was carried out at the operating temperature of 80 K, the current was limited from ≈ 80 kA to 1 kA. The third test was carried out at the temperature of 86 K and the maximum limited current was similar to the current in the second short-circuit test. After the third test, the SFCL temperature increased to the temperature above the critical temperature (89 K) of the SF12100 superconducting tape [7, 8].

TABLE I

Maximum current $I_{\max}$, critical current I_c and rated current I_r in the 6 kV/0.14 kA SFCL depending on the operating temperature (before the short circuit).

Operating temperature [K]	$I_{\max}$ [A]	I_c [A]	I_r [A]
40	6502	6502	1528
50	4746	4746	1100
60	3428	3428	737
72	1900	1900	402
80	1000	1000	188
86	998	262	62

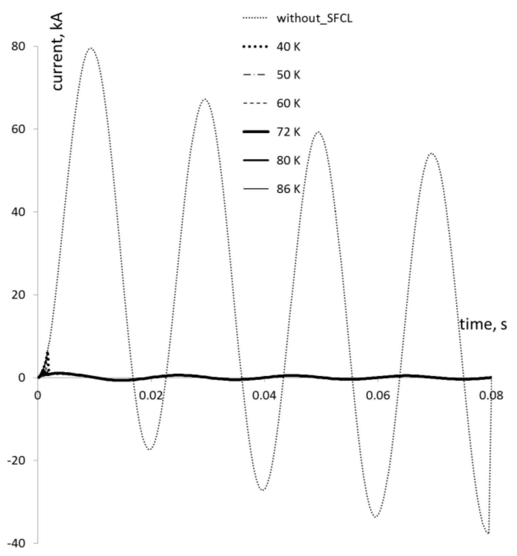

Fig. 1. Currents in the short-circuit circuit with the 6 kV/0.14 kA SFCL cooled to various operating temperatures and a circuit without a limiter (without SFCL). Time $\langle 0, 0.08\rangle$ s.

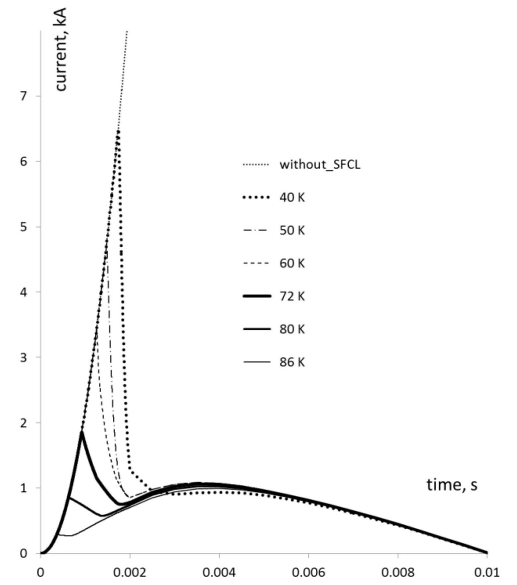

Fig. 2. As in Fig. 1 but for time $\langle 0, 0.01\rangle$ s.

Current courses during the short-circuit limitation largely depend on the initial operating temperature of the limiter, as shown in Figs. 1 and 2. The maximum currents in the short-circuit circuit with the SFCL placed in it during the limitation of the short circuit depend on the initial operating temperature of the limiter (Table I). The lower the operating temperature, the greater the maximum current. The maximum current increases as the critical current of the HTS tape increases with decreasing temperature from 80 K to 40 K. For temperatures above 80 K, the maximum short-circuit current remains around 1 kA, regardless of the decreasing critical current of the HTS tape.

The SFCL rated current increases as the temperature decreases in proportion to the critical current increase. This can be described by the following relation:

$$I_r = \frac{I_c}{3\sqrt{2}}, \tag{1}$$

where I_c is the critical current of the SFCL and I_r is the rated current of the SFCL (effective value). The number $\sqrt{2}$ results from the fact that I_c should be treated as the maximum value and I_r as the effective value in the sinusoidal current waveform. In turn, the number 3 results from the accepted multiplicity of the overload current. The limiter should operate only after exceeding the value of the overload current.

3. HTS tape temperature changes

Figure 3 presents the courses of temperature changes of the HTS tape of the limiter during the short circuit (0.00–0.08 s) and the cooling (0.08–3.00 s) as a function of the initial temperature of the 6 kV/0.14 kA SFCL.

The maximum temperature $T_{\max}$ to which the limiter (the HTS tape) heats up during the short circuit and the temperature of the limiter (the HTS tape) after 3 s, i.e., $T(3s)$, as a function of the initial temperature before the short circuit, are presented in Fig. 4. Figure 5 presents the average temperature increase, $\mathrm{d}T/0.01$ s as a function of the initial temperature before the short circuit.

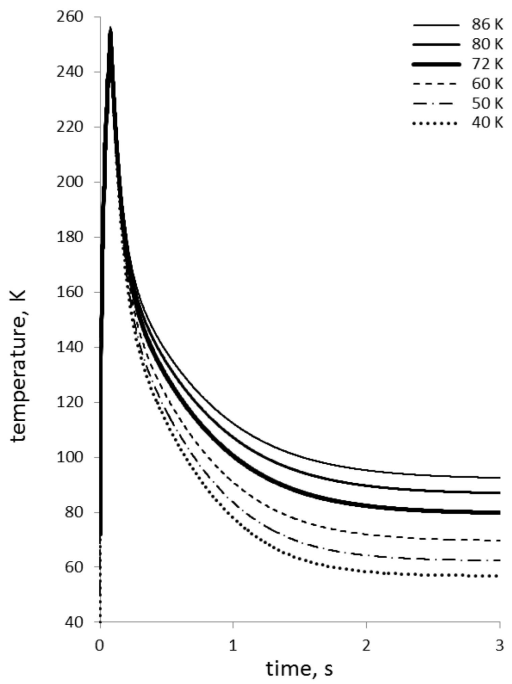

Fig. 3. HTS tape temperature during the short circuit (0.00–0.08 s) and the cooling (0.08–3.00 s) as a function of the initial operating temperature of the 6 kV/0.14 kA SFCL.

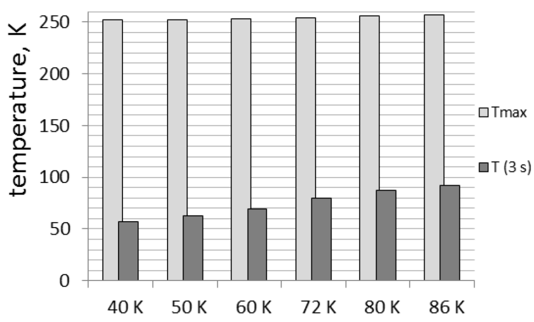

Fig. 4. Maximum temperature $T_{\max}$ to which the limiter (HTS tape) heats up during the short circuit and the limiter temperature (HTS tape) after 3 s, i.e., $T(3\ s)$ as a function of the initial temperature of the limiter.

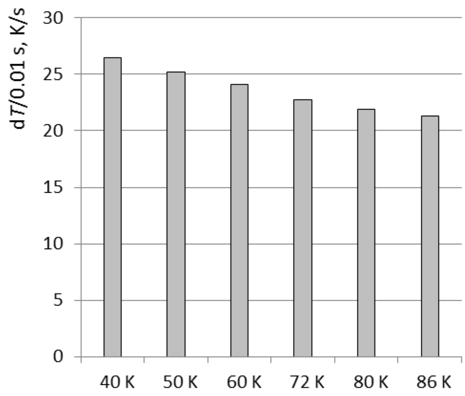

Fig. 5. Average temperature increase $\mathrm{d}T/0.01$ s as a function of the initial temperature of the limiter before the short circuit.

The lowering of the initial temperature has a slight effect on the maximum temperature $T_{\max}$ of the HTS tape. A initial temperature difference of 46 K (from 86 K to 40 K) results in a difference of ≈ 5 K at the maximum temperature. The maximum temperature does not exceed 256.5 K (for an initial temperature equals 86 K) (Fig. 4). From the point of view of the SFCL operation, the maximum temperature to which the HTS tape will be heated during the short circuit is very important. In the case of SF12100, exceeding 450 K is not permitted and may cause permanent damage to the limiter. Since the maximum temperature during the short circuit did not exceed 256.5 K, longer limiter operation can be considered as well. Lengthening the current limitation time will, however, increase the maximum temperature of the HTS tapes and extend the cooling time of the limiter. The average temperature increase during short-circuit limitation at 40 K is 26.5 K/0.01 s and during short-circuit limitation at 86 K it decreases to 21.3 K/0.01 s.

The percentage increase in temperature after short circuit $\mathrm{d}T$ (in %) (after 3 s) as a function of the initial temperature before the short circuit

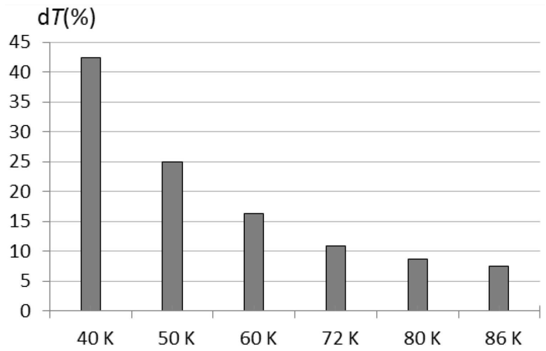

Fig. 6. Percentage increase in temperature after short circuit $\mathrm{d}T$ (in %) as a function of the initial temperature of the limiter before the short circuit.

is presented in Fig. 6. The lowering of the initial temperature significantly increases the percentage rise of temperature after the short circuit $\mathrm{d}T$. Thus, for the initial temperature of 86 K one has $\mathrm{d}T = 7.54\%$ and at the initial temperature of 40 K, $\mathrm{d}T$ increases to 42.32%.

4. Conclusions

The maximum temperature of the superconducting tapes, in the 6 kV/0.14 kA SFCL, when the short-circuit current is switched off by an external switch ($t = 0.08$ s) does not exceed 256.5 K.

Since the permissible temperature of the superconducting tape SF12100 should not exceed 450 K and the maximum temperature during the short circuit did not exceed 256.5 K, this indicates that even longer 6 kV/0.14 kA SFCL operation may be considered. Extending the limiter operation time will, however, increase the maximum HTS tape temperature. Moreover, the SFCL cooling time after short circuit will also be extended.

The operating current can be increased many times by lowering the limiter's operating temperature. Lowering the SFCL's operating temperature has, in fact, little effect on the maximum HTS tape temperature during the short circuit. The maximum temperature is determined mainly by the time of the current limitation.

Acknowledgments

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