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Superconducting Surge Current Limiter

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Abstract: A superconducting fault current limiter (SFCL) for medium voltage networks cooled by a cryocooler was designed, built and tested by the current author. For the construction of this limiter, a high-temperature second generation superconducting tape (HTS 2G)—SF12100—was used. In this limiter, it is possible to change the working temperature. The possibility of changing the operating temperature allows for adjusting the parameters of the limiter to the electric power needs. Adjusting the parameters of the limiter to the power needs is a key problem to solve, resulting from the ambiguous characteristics of HTS tapes. Cooling with a cryocooler is the only solution in the case of a limiter for power industry applications. The electric power mechanism does not tolerate any liquids. After analyzing the experimental results and after analyzing the results from the numerical models of the limiter, the concepts of using superconductors to limit current in the power industry were changed: the transition from a superconducting fault current limiter (SFCL) to a superconducting surge current limiter (SSCL). Transition to the limiter operation system—surge current limitation—is associated with the reduction in the limiter operation time. The advantages of the transition from the SFCL to SSCL work system are presented.

Keywords: SFCL; SSCL; HTS tape; short-circuit current

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1. Introduction

A superconducting fault current limiter—SFCL—for medium voltage networks cooled by a cryocooler, financed by the National Fund for Environmental Protection and Water Management and the National Center for Research and Development, under the project: GEKON2/O2/267193/13/2015, was designed, built and tested with the participation of the author [1–3].

This SFCL is built with the use of a second generation high-temperature superconducting tape (HTS 2G)—SF12100 (SuperPower Inc., 21 Airport Road, Glenville, NY 12302, USA) Both superconducting windings of the limiter have 28.5 turns of the superconducting tape SF12100. Each winding has 66 m of the HTS tape wound in opposite directions and connected in parallel. The terminals of the windings are situated on the internal side of the windings structure and are connected to the current leads [3]. The currents leads and the superconducting windings are cooled by cryocooler KDE400SA. The ceramic insulators of the current leads assure good thermal transfer and electrical insulation. The fiberglass structure of the superconducting windings is light and nonconductive of electrical current. The copper plates (76.8 kg) incised into vertical stripes ensure good conductive cooling of the windings and reduce the eddy currents' losses [3]. The SFCL winding diameter is 0.736 m and the winding height is 0.44 m. A LakeShore 218 Temperature Monitor with Cernox sensors is used to measure the temperature of SFCL. Cernox sensors are attached to the copper plates.

Contrary to the previous limiters for medium voltage networks built and tested by the author [4–9], in which a cooling system in a liquid nitrogen bath was used, with a constant operating temperature of the limiter of 77.4 K, there is a possibility of changing the operating temperature.

Table 1 shows the SFCL design parameters according to [3]. In fact, the electrical parameters of the constructed SFCL are better than the design parameters [3] (Table 1). The reason for this is described in Chapter 4.

Table 1. Parameters of SFCL windings (2× SF12100 HTS tapes) at 77.4 K [3].

Parameters Description	Value
nominal voltage	6 kV
nominal current	140 A
overload current	420 A
critical current	600 A
voltage per 1 m tape length	52.5 V
length of HTS tape per winding	66 m
length of single turn	2.31 m
winding height	0.44 m
winding diameter	0.736 m
number of turns	28.5

As seen in the References, publications [1–17] are used in this article. I included another ten new publications from 2021 [18–27] (selected out of many publications), which shows that the topic of SFCL is still relevant and many people around the World are researching it.

The article [20] presents the idea of the SFCL design, similar to the described limiter, but the made, small limiter is similar to that constructed by my laboratory in 2013. The described limiter is to be used in electric propulsion aircrafts. High-voltage limiters are described in articles [18,23,27]. The articles [22,27] present the limiter operating in the DC system. Current limiting in a DC system is not a problem. The problem is the disconnection of the limiter because the limited current does not cross zero, as in the case of an AC system. The articles [18,19,21,26,27] describe a different design of the limiter winding than in the case of the SFCL from this article. In articles [24,25], some problems related to the operation of medium voltage SFCLs were described. In the selected articles, the limiters were not cooled with the use of a cryocooler. These limiters were cooled mainly with liquid nitrogen.

2. Conclusions after Short-Circuit Tests

The SFCL tested in the Short-Circuit Endurance Testing Laboratory of the Institute of Electrical Engineering in Warsaw was the third medium voltage limiter built by the author [1–3] (Figure 1).

Previous limiters (Figure 2) were also tested in this Short-Circuit Endurance Testing Laboratory. The analysis of the causes of the failure of the two previous limiters allows one to design a good limiter, which was not damaged after three short-circuit tests. These were not "laboratory" short-circuit tests. The power of the short-circuit generator was 2.5 GVA. The short-circuit current, without limiter, was set to 81.24 kA.

Before the short-circuit test, all sensors were disconnected. This was due to the enormous power generated in the limiter during the limitation of the short-circuit (Figure 3) and the medium voltage that could damage the measuring instruments. A few minutes after the sensors had been disconnected, a short-circuit test was carried out. A few minutes after the short-circuit test, the measuring sensors were turned on and the data were saved. If the temperature of the limiter was lower than the critical temperature of the HTS tape, the measuring instruments were disconnected again and another short-circuit test was performed.

Three short-circuit tests were successfully carried out, starting at T_0 = 72 K (Figure 4). The second short-circuit test started at the limiter temperature T_0 = 80 K (Figure 5), and the third one at the temperature T_0 = 86 K (Figure 6). After the third short-circuit test, the temperature of the limiter rose to a level higher than the critical temperature of the HTS tape and the short-circuit tests were completed.



Figure 1. The third medium voltage SFCL tested in the Short-Circuit Endurance Testing Laboratory of the Institute of Electrical Engineering in Warsaw.

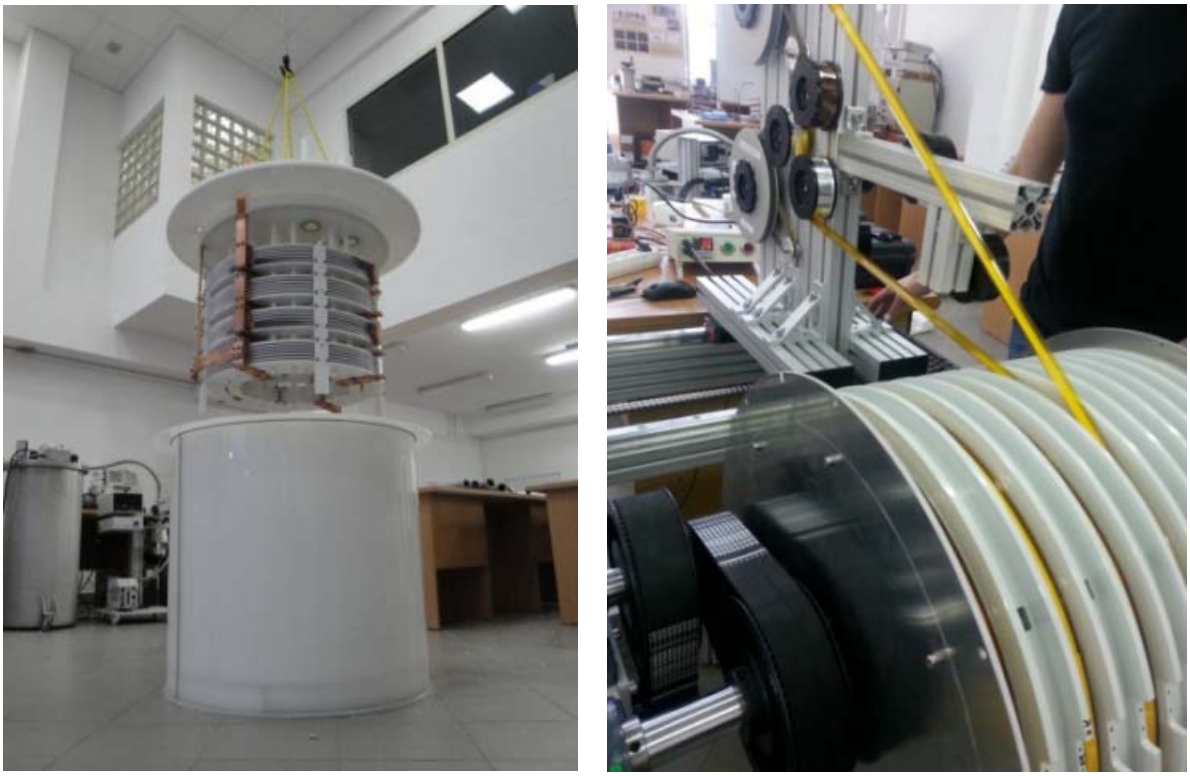


Figure 2. The first and second medium voltage SFCL [4–9].

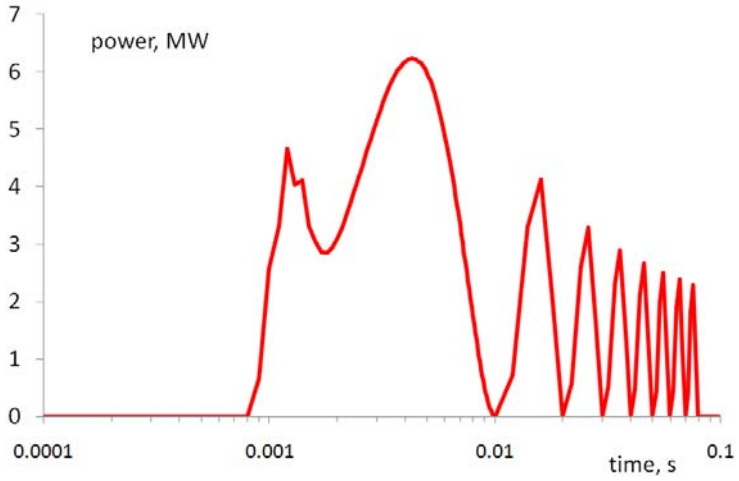


Figure 3. Changes of the power generated in the HTS tape of the limiter during a short-circuit (0–0.08 s) for the initial temperature of the limiter before short-circuit = 72 K (first short-circuit test—Figure 4).

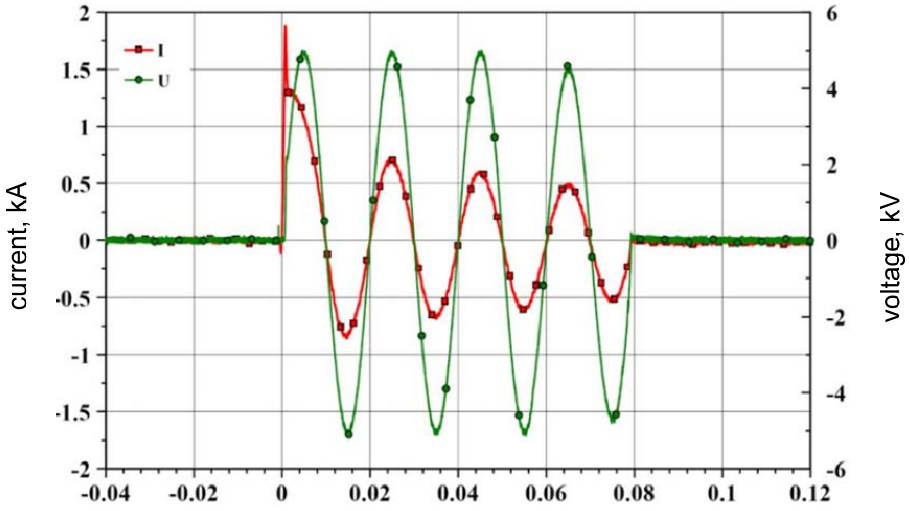


Figure 4. The course of the short-circuit current and the measured voltage at the limiter—short-circuit test No. 1. (T_0 = 72 K). I—current, U—voltage.

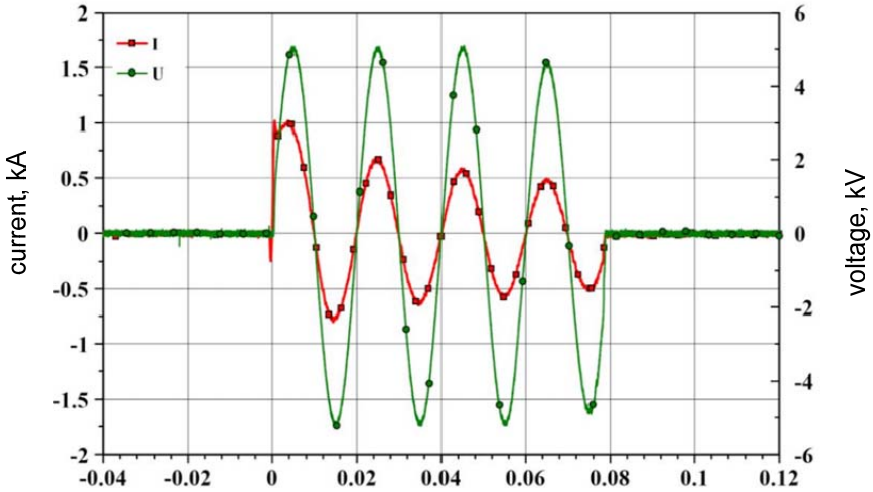


Figure 5. The course of the short-circuit current and the measured voltage at the limiter—short-circuit test No. 2. (T_0 = 80 K). I—current, U—voltage.

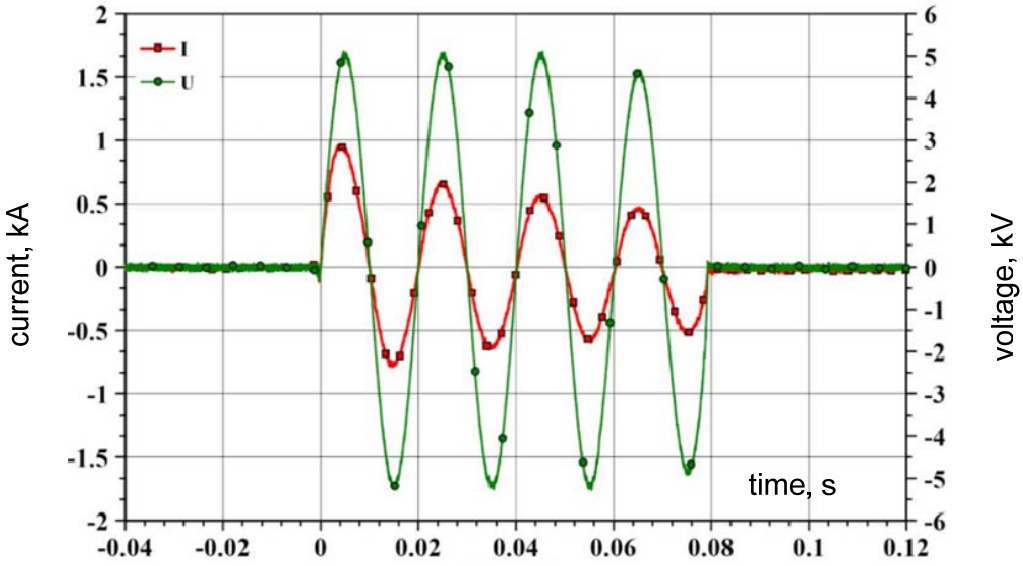


Figure 6. The course of the short-circuit current and the measured voltage at the limiter—short-circuit test No. 3. (T_0 = 86 K). I—current, U—voltage.

Figure 7 shows short-circuit current waveform in the tested system without SFCL and with SFCL (short-circuit test No. 1, T_0 = 72 K, Figure 4).

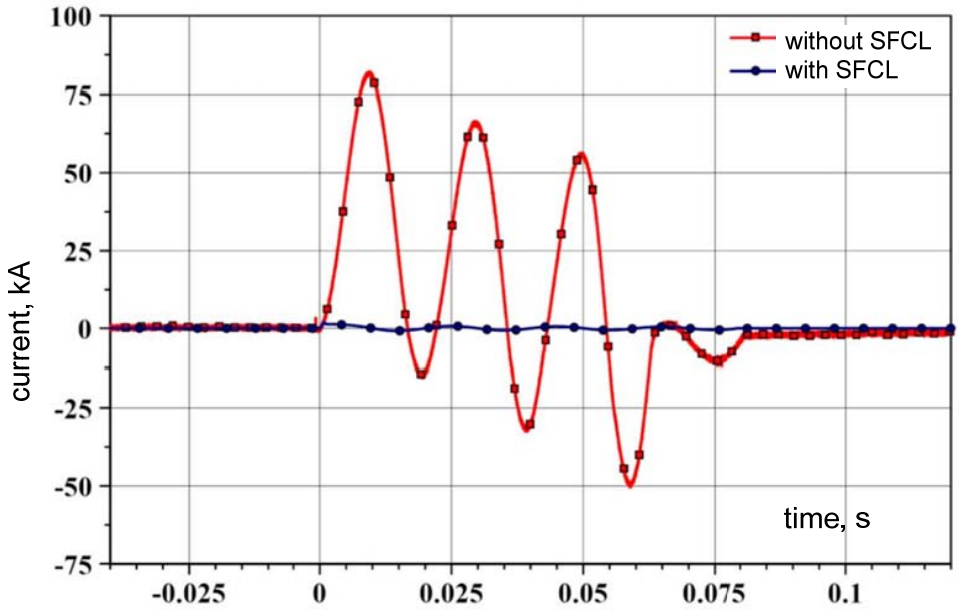
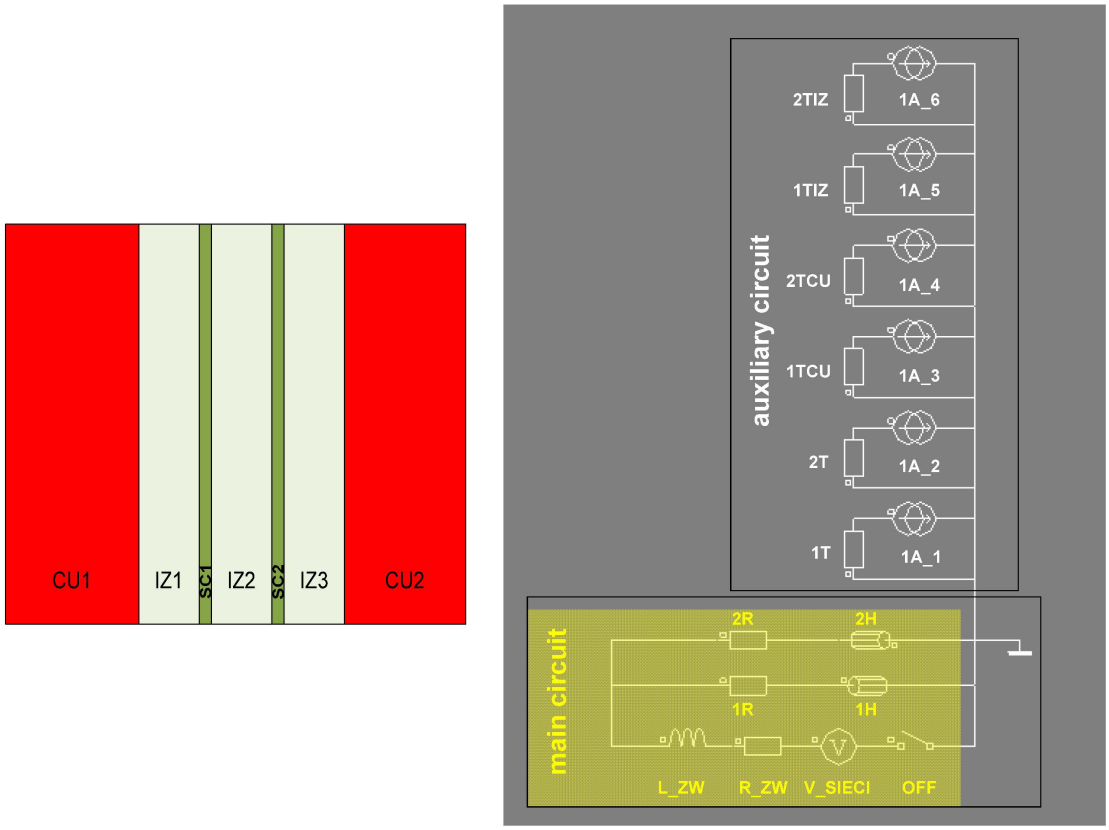


Figure 7. Short-circuit current waveform in the tested system without SFCL and with SFCL—short-circuit test No. 1. (T_0 = 72 K).

During the short-circuit tests in the Short-Circuit Endurance Testing Laboratory, only the current and voltage at the limiter were recorded (Figures 4–7). Therefore, a numerical analysis of the operation of the limiter was necessary [1,2,7,11,12]. The geometry and electrical circuit diagram of the numerical model are presented in Figure 8. The geometric parameters of the areas of the numerical model are shown in Table 2. The numerical model of the SFCL was developed using the FLUX2D program. The numerical model allows the analysis of electromagnetic and thermal phenomena occurring in a SFCL located in the short-circuit circuit.



(**a**) (**b**)

Figure 8. (**a**) Geometry of the numerical model (proportions are not correct). The sizes are in Table 2. (**b**) Electrical circuit diagram of the numerical model.

Table 2. Geometric parameters of the areas of the numerical model.

	SC1	SC2	CU1	CU2	IZ1	IZ2	IZ3
material	SF12100	SF12100	copper	copper	insulation	insulation	insulation
inner radius (m)	0.368	0.368605	0.3665	0.36971	0.3675	0.368105	0.36871
thickness (m)	0.000105	0.000105	0.001	0.001	0.0005	0.0005	0.0005
height (m)	0.4395	0.4395	0.4395	0.4395	0.4395	0.4395	0.4395
number of turns	28.5	28.5	-	-	-	-	-

Electromagnetic calculations were carried out in the transient magnetic module coupled with the external circuit and in the transient thermal module. In each calculation step, the temperature of the HTS windings was calculated and the resistance of these windings in the external circuit was changed depending on the current and temperature, taking into account the heat distribution between the areas SC1, SC2 and IZ1, IZ2, IZ3, CU1, CU2 (Figure 8a). The necessary parameters (1T, 2T, 1TIZ, 2TIZ, 1TCU, 2TCU) used for the calculation of the heat balance are stored in additional auxiliary electrical circuits (Figure 8b). Table 3 presents the parameters used in the SFCL numerical model, defined by existing functions or defined by a user function (User ()). Some parameters have values assigned to them.

During the first test, at the 72 K initial temperature, the current was limited in the short-circuit circuit from 81.24 kA (without the limiter) to a maximum of 1.9 kA (Figures 4, 7, 9 and 10). During the second short-circuit test, which was carried out at the 80 K initial temperature (Figures 5, 9 and 10), the current was limited from 81.24 kA to 1 kA. The third test was carried out at the 86 K initial temperature and the maximum limited current was similar to the current in the second short-circuit test (Figures 6, 9 and 10).

Table 3. Parameters of numerical model.

Name	Definition
1R	Max(0.00000000001, R1)
2R	Max(0.00000000001, R2)
R_ZW	0.00776
L_ZW	0.00035
1T	Max(T0, E1)
2T	Max(T0, E2)
1TCU	Max(T0, E1CU)
2TCU	Max(T0, E2CU)
1TIZ	Max(T0, E1IZ)
2TIZ	Max(T0, E2IZ)
E1	User(11, I(1R), T1, U(1R), SK, TCU1, TIZ1, T0)
E2	User(12, I(2R), T2, U(2R), SK, TCU2, TIZ2, T0)
E1CU	User(13, 0, TCU1, 0, SK, T1, TIZ1, T0)
E2CU	User(14, 0, TCU2, 0, SK, T2, TIZ2, T0)
E1IZ	User(15, 0, TIZ1, 0, SK, T1, T2, T0)
E2IZ	User(16, 0, TIZ2, 0, SK, T1, T2, T0)
R1	User(1, I(1R), T1, U(1R), SK, 0, 0, T0)
R2	User(2, I(2R), T2, U(2R), SK, 0, 0, T0)
T0	72, 80, 86
T1	U(1T)
T2	U(2T)
TCU1	U(1TCU)
TCU2	U(2TCU)
TIZ1	U(1TIZ)
TIZ2	U(2TIZ)
SK	0.00001 · Valid(TIME, 0, 0.00301) + SK2
SK2	0.0005 · Valid(TIME, 0.00301, 0.1301) + 0.005 · Valid(TIME, 0.1301, 31)
1A_1–1A_6	1
V_SIECI	Sqrt(2) · 3520 · Sin(314.159265 · TIME)

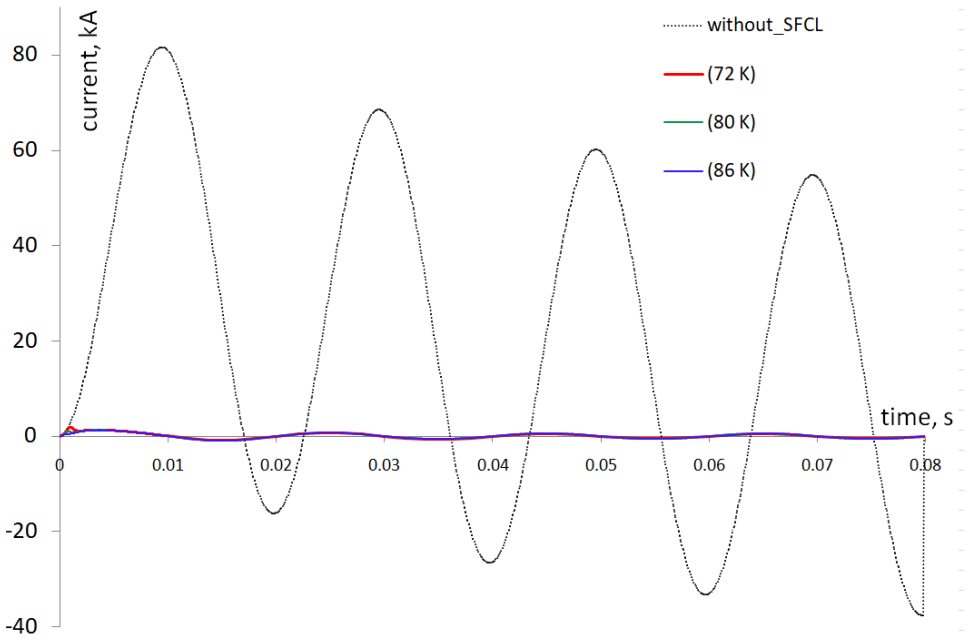


Figure 9. Currents in the short-circuit circuit with a limiter (SFCL) placed in it, cooled to 72 K, 80 K and 86 K, and in the circuit without the limiter (without_SFCL). Time from 0 s to 0.08 s (numerical analysis).

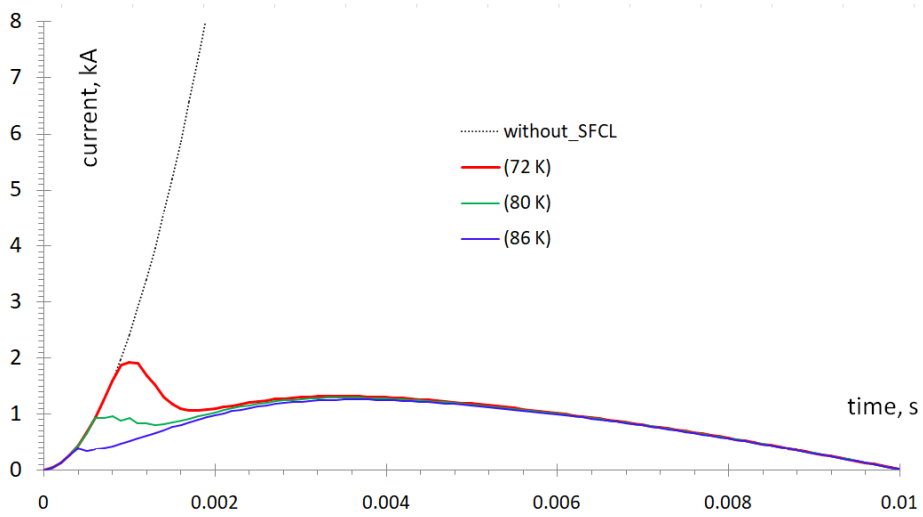


Figure 10. Currents in the short-circuit circuit with a limiter (SFCL) placed in it, cooled to 72 K, 80 K and 86 K, and in the circuit without the limiter (without_SFCL). Time from 0 s to 0.01 s (numerical analysis).

The waveforms of the current during the limitation of the short-circuit depend largely on the initial temperature of the limiter as shown in Figures 4–7, 9 and 10. The lower the initial temperature, the greater the maximum current. The maximum current increases with the increase in the critical current when the temperature is less than 80 K. For temperatures above 80 K, the maximum short-circuit current remains around 1 kA, regardless of the decreasing critical current (Figure 10).

Changing the temperature changes the parameters of the HTS tape. Figure 11 shows the relationship between the critical current of the SF12100 tape and the temperature [1–3,14]. Lowering the temperature from 77.4 K to 72 K increases the critical current of the SF12100 tape 1.5 times (in relation to 77.4 K). At the temperature of 80 K, the multiplicity of the critical current of the SF12100 tape (in relation to 77.4 K) is 0.7. If we assume that the operating temperature of this limiter is 72 K, then after the short-circuit current is reduced, after the limiter temperature rises from 72 K to 80 K, the limiter parameters decrease by more than twice (1.5/0.7). In the case of laboratory tests, it is of little importance; in the case of using a limiter in the power industry, it is crucial.

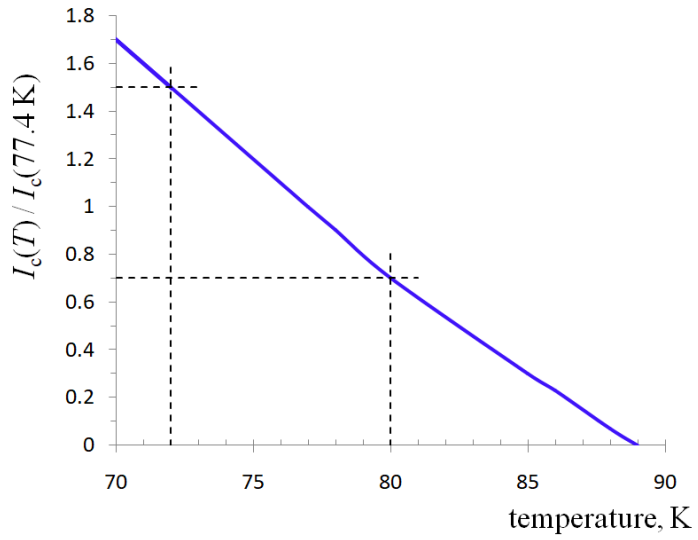


Figure 11. Multiplicity of the critical current with respect to the critical current at the temperature of 77.4 K for the SF12100 tape as a function of temperature.

3. Analysis of the Operation of the Limiter

In the analysis, the 72 K temperature was assumed as the base operating temperature of the limiter. The tested SFCL limited the short-circuit current over 0.08 s. The limitation time was determined so that the temperature of the superconducting windings (HTS tapes) during current limitation did not exceed a certain value. The SF12100 tape temperature must not exceed 420 K. It is related not only to the construction of the tape, but also to the material used to solder the tape. After 0.08 s, the limiter was disconnected by a conventional switch. Figure 12 shows the temperature change of the HTS tape during a short-circuit lasting 0.08 s (as during the first short-circuit test) and during longer short-circuits lasting 0.1 s and 0.12 s.

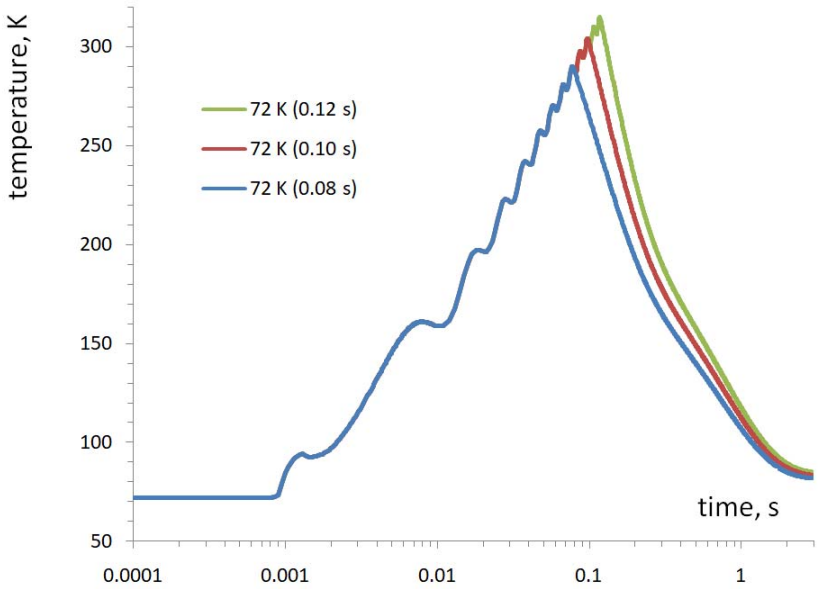


Figure 12. Changes in temperature of the limiter HTS tape during short circuit (0–0.08 s) and cooling (0.08–3 s)—"72 K (0.08 s)" and during short circuit (0–0.1 s) and cooling (0.1–3 s)—"72 K (0.1 s)" and during short-circuit (0–0.12 s) and cooling (0.12–3 s)—"72 K (0.12 s)" for the initial temperature of the limiter before short-circuit = 72 K.

In Table 4, the values of the maximum temperature T_{max} and the end temperature $T_{(3s)}$ are given according to Figure 12. The end temperature $T_{(3s)}$ is the temperature after 3 s counted from the beginning of the short-circuit test (not from the end). From the (design) assumption, the maximum temperature of the HTS limiter cannot exceed 420 K. Additionally, this is the case in three cases of short-circuit current limitation (Figure 12). The maximum temperature of the limiter is the temperature of the HTS tape. The end temperature $T_{(3s)}$ is understood as the temperature of the entire limiter. The differences in the final temperatures are small compared to the differences in the maximum temperatures, which can be seen in Figure 12 and in Table 4. The differences in the final temperatures have an impact on the operation of the limiter in the electric power system.

Table 4. Maximum temperature T_{max} and end temperature (after 3 s) $T_{(3s)}$ of the limiter acc. Figure 12 and cooling time to T_0. T_0—initial temperature, t_{zw}—short-circuit duration.

Short-Circuit	T_0	t_{zw}	T_{max}	$T_{(3s)}$	Cooling Time to T_0
72 K (0.08 s)	72 K	0.08 s	290 K	81.7 K	6300 s
72 K (0.10 s)	72 K	0.10 s	304 K	83.2 K	7320 s
72 K (0.12 s)	72 K	0.12 s	315 K	84.7 K	8400 s

3.1. Analysis of the Results (Figures 12 and 13, Tables 4 and 5) in the Laboratory Context

The limiter works satisfactorily. It returns to the superconducting state quickly after the short-circuit is reduced (Figure 13). Changing the short-circuit current limiting time does not change the (laboratory) parameters of the limiter. The increase in the time of limiting the current minimally increases the time of the limiter's recovery from the resistive state to the superconducting state (Table 5).

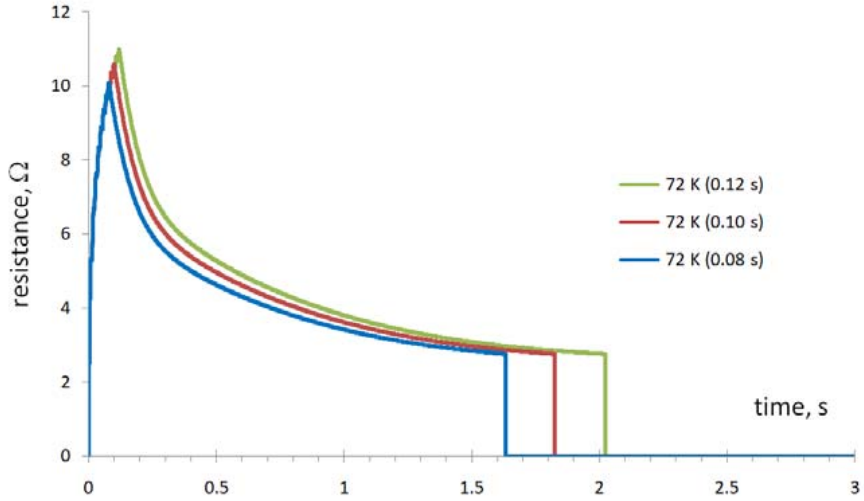


Figure 13. Changes of the HTS tape resistance of the limiter during short circuit (0–0.08 s) and cooling (0.08–3 s)—"72 K (0.08 s)" and during short circuit (0–0.1 s) and cooling (0.1–3 s)—"72 K (0.1 s)" and during short-circuit (0–0.12 s) and cooling (0.12–3 s)—"72 K (0.12 s) " for the initial temperature of the limiter before short-circuit = 72 K.

Table 5. Maximum resistance R_{max} of the limiter during short-circuit limitation and time of HTS tape recovery from the resistive state to the superconducting state $t_{R\text{-}N}$ (after the short-circuit ends) acc. Figure 13. T_0—initial temperature, t_{zw}—short-circuit duration.

Short-Circuit	T_0	t_{zw}	R_{max}	$t_{R\text{-}N}$
72 K (0.08 s)	72 K	0.08 s	10.08 Ω	1.55 s
72 K (0.10 s)	72 K	0.10 s	10.59 Ω	1.73 s
72 K (0.12 s)	72 K	0.12 s	10.94 Ω	2.00 s

3.2. Analysis of the Results (Figures 12 and 13, Tables 4 and 5) in the Context of the Electric Power System

The change of the limiter parameters after limiting the short-circuit in terms of the electric power system is decisive.

The relationships between I_c, I_r and $I_{r\,max}$ are given by the following formulas:

$$I_{r\,max} = \sqrt{2} I_r \quad (1)$$

and

$$I_c = 3 I_{r\,max} \quad (2)$$

The number 3 is the assumed value related to the multiplicity of overload currents in the power system.

In conventional devices, the sequence of adjustments to the operating parameters of the limiters starts with I_r. The RMS value of the rated current is a property of the system for which the limiter is designed. The maximum value of the rated current multiplied by 3 (the assumed value) determines the threshold of the short-circuit current limiter.

From the point of view of the operation of a superconducting limiter, the parameters $I_{r\,max}$ and I_c are important. In the case of a superconducting limiter, the initial data of the limiter are its activation threshold—critical current I_c.

The parameters of the limiter connected to the protection system after limiting the short circuit have changed (Figure 14, Table 6). After a short-circuit lasting 0.08 s, I_c of the limiter is not much higher than $I_{r\,max}$ before the short-circuit. The limiter will work correctly at the rated current. If the maximum of the rated current is exceeded by 13% (I_c = 113% $I_{r\,max}$), the limiter will start to limit the current, and this should only occur after 300% $I_{r\,max}$. After short-circuits lasting 0.1 s and 0.12 s, the I_c of the limiter is lower than $I_{r\,max}$ before the short-circuit. The limiter will therefore start to limit the current to a value lower than the rated current. To sum up, the conclusion is as follows: after limiting the short-circuit, lasting for 0.08 s, 0.1 s and 0.12 s, the limiter can be connected back to the protection system, after cooling it to the temperature before the short-circuit, in the discussed case—to the temperature = 72 K. The cool-down time is long and is(according to the data in Table 4) from 6300 s to 8400 s.

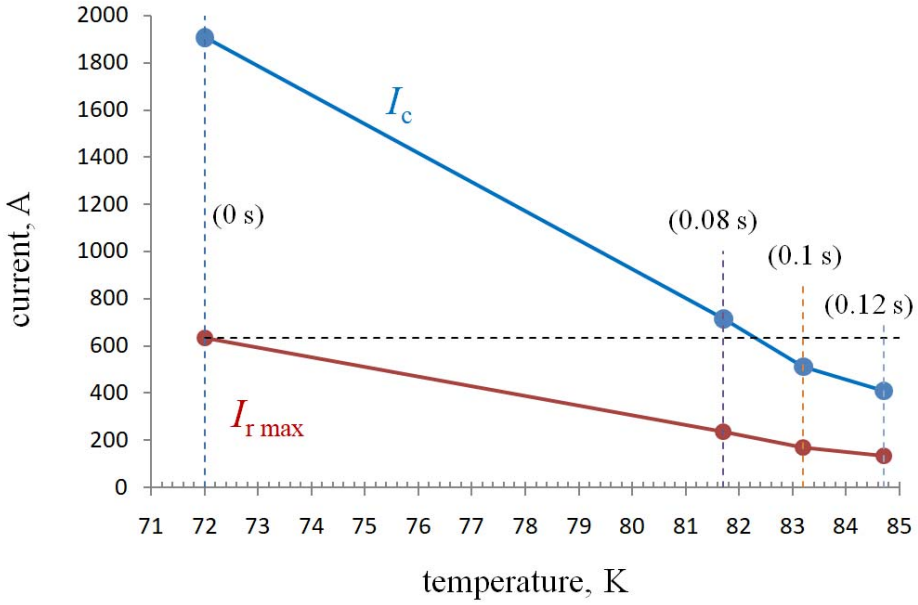


Figure 14. Basic parameters of the limiter—I_c and $I_{r\,max}$ before short-circuit (0 s) and after short-circuits lasting: 0.08 s, 0.1 s and 0.12 s, in accordance with Table 6.

Table 6. I_c—critical current of the limiter as a function of temperature T_0. Rated current of the limiter I_r—rms value, $I_{r\,max}$—the maximum of the rated current.

T_0	I_c	I_r	$I_{r\,max}$
72 K	1909 A	450 A	636 A
81.7 K	718 A	169 A	239 A
83.2 K	514 A	121 A	171 A
84.7 K	412 A	97 A	137 A

4. Cryocooler in the Power System

In HTS 2G tapes (second generation), due to the complex deposition processes of the material, it is difficult to maintain homogeneous superconducting properties—i.e., the critical current. Figure 15 shows the characteristics of one of the HTS 2G tapes (SF12050), which was used to build the previous current limiters (Figure 3) [4–9]. There are significant differences in the value of the critical current measured every 5 m of the tape [7,10,13,14]. The minimum value of the critical current for this tape (200 m) is 256 A and the maximum value of the critical current is ~330 A. For a 200 m spool, the nominal critical current is the

lowest critical current value out of 40 measurements every 5 m of tape of spool. This is of colossal importance. If we unwind the first 30 m from this spool, this piece will have a critical current = 256 A. The next 30 m of tape from this spool will have a critical current of ~300 A.

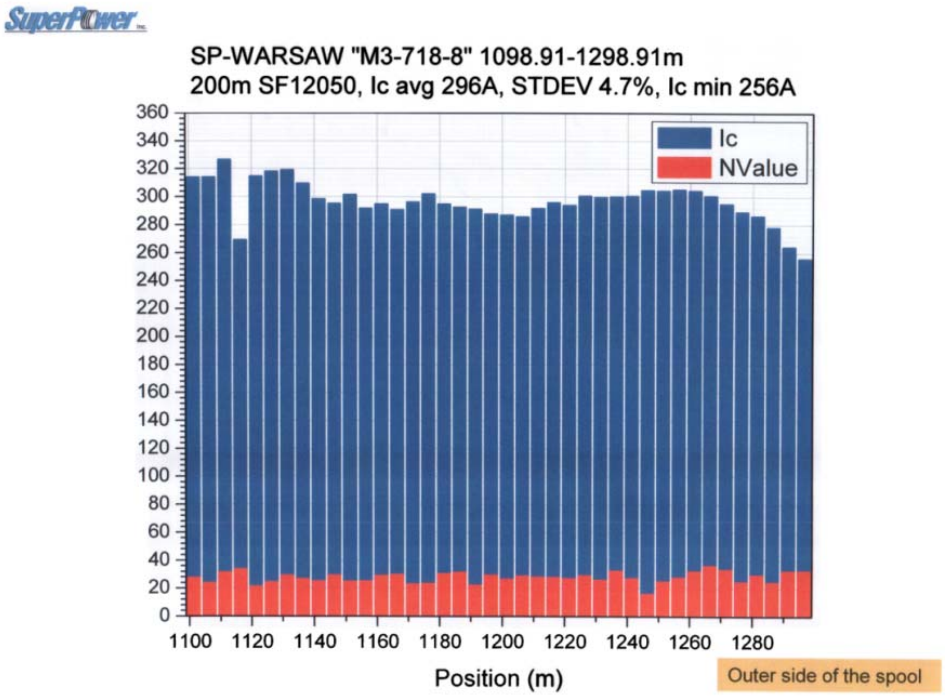


Figure 15. Significant differences in the value of the critical current measured every 5 m by the manufacturer of the HTS 2G tape. Liquid nitrogen temperature, natural field [7,14].

Such a problem appeared in the discussed limiter. After designing the limiter for the set value of the rated current I_r, an HTS tape with a specific value of the critical current was purchased. However, as shown in Figure 15, it was the minimum value of the critical current.

After building the limiter and conducting short-circuit tests, we obtained data that allowed us to verify the numerical models. It turned out that the critical current of the limiter (the HTS tape used in the limiter) is much higher than the current value provided by the manufacturer for the entire spool with the HTS tape. From a laboratory point of view, this is not a problem and even an advantage. From the power engineering point of view, such a limiter cannot be installed in the planned place with the adopted rated current I_r, because it must operate after exceeding the maximum $I_{r\,max}$ three times. If it has better parameters, i.e., I_c is much greater than 3 $I_{r\,max}$, some of the short-circuits will not be limited.

In the case of a bath-cooled limiter, with a constant temperature, this problem cannot be solved. In the case of contact cooling with the use of a cryocooler, by changing the temperature, the parameters of the limiter can be easily adjusted to those required in the system. Thus, the value of the limiter critical current I_c, which determines the limiter parameters, can be changed.

By changing the operating temperature of the limiter through a cryocooler, you can change the parameters of the limiter, which is an advantage. The main disadvantage of contact cooling is the small power of the cryocooler—that is, the long cooling time.

The limiter examined by the author was not only short-circuit tested, but was installed in the switching station (for a week). This confirmed that cooling with a cryocooler is the only solution in the case of the limiter for power industry applications. One should forget about cooling with the use of cryogenic liquids; the electric power engineering does not tolerate any liquids. If the limiter were cooled with liquid nitrogen (lH_2), there would be

no room for a limiter to be installed at the switching station, and there would be no consent from the power industry. The liquid helium (lHe) in the compressor in the cryocooler moves in a closed area, is isolated from the surroundings and is not a problem in the power industry. If the compressor (lHe) for the cryocooler was water-cooled (H_2O), there would also be no water in the vicinity of the limiter installation, nor would there be any approval of the electric power engineers for the installation. The compressor (lHe) in the cryocooler of the installed limiter was cooled by an electrically driven fan.

5. Changing the Principle of Operation of the Limiter

After analyzing the experimental results (short-circuit tests) and after analyzing the results of the numerical models of the limiter (models verified by the results of short-circuit tests), I changed the concepts of using superconductors to limit current in the power industry: from the Superconducting Fault Current Limiter (SFCL) to Superconducting Surge Current Limiter (SSCL).

The superconducting limiter will be connected in series with an electronic switch, e.g., thyristor. After limiting the surge current, the electronic circuit breaker will disconnect the superconducting limiter, and further limitation of the short-circuit current will take place in a conventional system, which will be turned on after disconnecting the SFCL. This change will reduce the heating time of the SFCL limiter from 0.08 s to 0.01 s. Figure 16 shows a comparison of the HTS tape temperature waveforms during short-circuits in which the limiter is disconnected after 0.01 s and after 0.08 s.

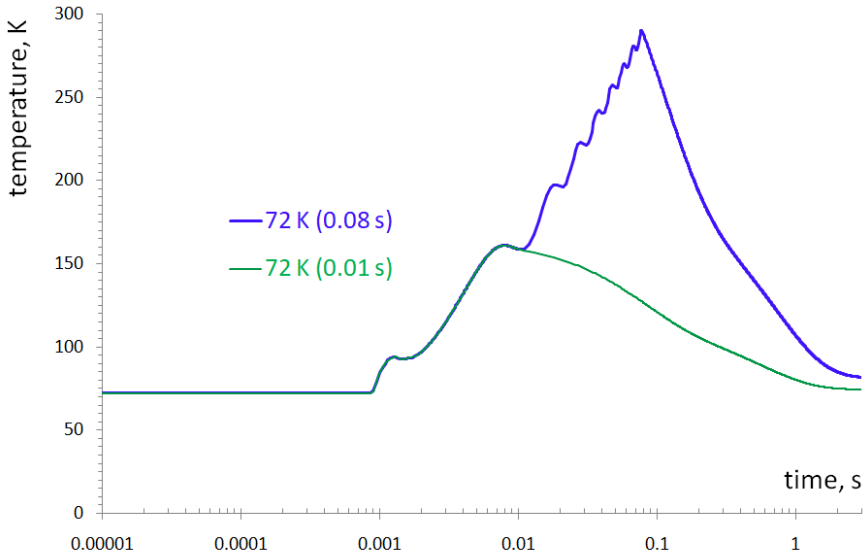


Figure 16. Temperature changes of the limiter HTS tape during short-circuit (0–0.08 s) and cooling (0.08–3 s)—"72 K (0.08 s)" and during short circuit (0–0.01 s) and cooling (0.01–3 s)—"72 K (0.01 s)" for the initial temperature of the limiter before short-circuit = 72 K.

In Table 7, the values of the maximum temperature T_{max} and end temperature $T_{(3s)}$ are given according to Figure 16. The maximum short-circuit temperature of 72 K (0.01 s) is much lower than the T_{max} of 72 K short-circuit (0.08 s). The end temperature $T_{(3s)}$ after a short-circuit of 72 K (0.01 s) is significantly lower than $T_{(3s)}$ after a short-circuit of 72 K (0.08 s).

Table 7. Maximum and final temperature of the limiter acc. Figure 16.

Short-Circuit	T_0	t_{zw}	T_{max}	$T_{(3s)}$	Cooling Time to T_0
72 K (0.01 s)	72 K	0.01 s	161 K	74.3 K	1500 s
72 K (0.08 s)	72 K	0.08 s	290 K	81.7 K	6300 s

Figure 17 (and Table 8) shows the basic parameters of the limiter—I_c and $I_{r\,max}$ before short-circuit (0 s) and after short-circuits lasting 0.01 s and 0.08 s. After limiting the short-circuit, the limiter connected to the protection system changes the parameters as a result of the limiter temperature increase. After a short-circuit lasting 0.08 s, the I_c of the limiter is not much higher than $I_{r\,max}$ before the short-circuit. The limiter will work correctly at the rated current. The limiter will start to limiting current at 113% $I_{r\,max}$, but this should only occur after 300% $I_{r\,max}$. After a short-circuit lasting 0.01 s, the I_c of the limiter is 231% higher than the $I_{r\,max}$ before the short-circuit. 231% is less than the required 300% but this may cold be an acceptable value compared to 113% for a 72 K (0.08 s) short-circuit.

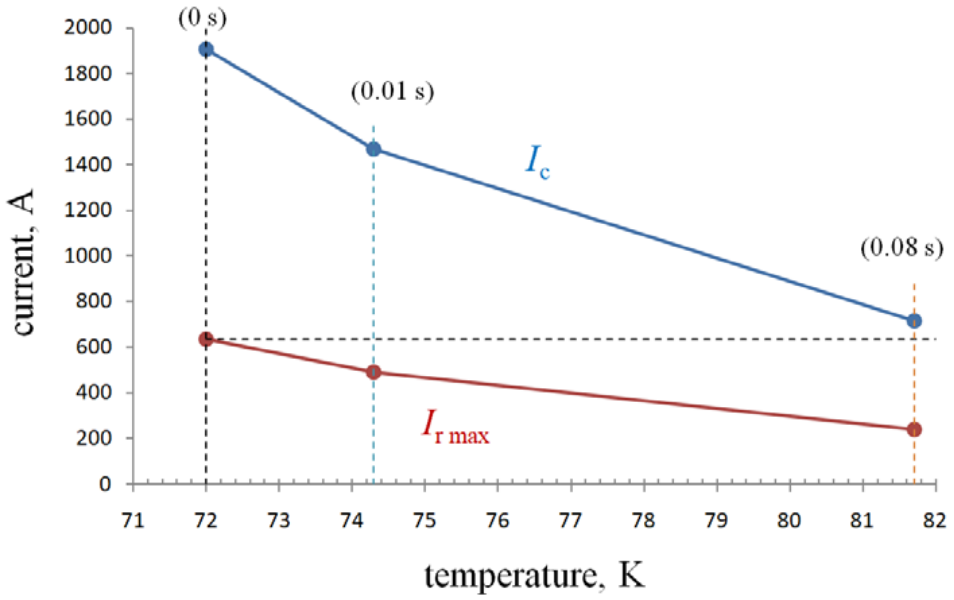


Figure 17. Basic parameters of the limiter—I_c and $I_{r\,max}$ before short-circuit (0 s) and after short-circuits lasting: 0.01 s and 0.08 s, in accordance with Table 8.

Table 8. I_c—critical current of the limiter as a function of temperature T_0. Rated current of the limiter I_r—rms value, $I_{r\,max}$—the maximum of the rated current.

T_0	I_c	I_r	$I_{r\,max}$
72 K	1909 A	450 A	636 A
74.3 K	1471 A	347 A	490 A
81.7 K	718 A	169 A	239 A

The second, very significant difference is presented in Figure 18 and Table 9. The most important thing is that after a short-circuit of 72 K (0.01 s), the limiter returns from the resistive state to the superconducting state after less than 1 s, and exactly after = 0.55 s. This is of fundamental importance from the point of view of power engineering. The power system, after disconnecting during the fault, is reconnected after less than 1 s. Therefore, this 72 K (0.01 s) limiter can be reconnected to the system after less than 1 s. Obviously, the limiter will not work like before when limiting short-circuit. It will start working when the current exceeds 1471 A, and it should start working only when the current exceeds 1909 A. Of course, the overload current (here assumed as 3) is a conventional value. Additionally, it should be established with electric power engineering, whether such a temporary reduction in the multiplication factor of the overload current is permissible or not. You can increase the multiplicity of the overload current before the short-circuit (by setting the parameters of the limiter) and then, after the short-circuit, the multiplicity will be higher than 231%. After a short-circuit, you need the limiter to quickly return to the temperature that it was before the short-circuit. In the discussed case, up to the temperature of 72 K. In the constructed limiter, the return to the temperature = 72 K (from 74.3 K to 72 K) takes 1500 s (Table 7). If

we added a second cryocooler to the cooling system, the cooling time would be reduced to 840 s.

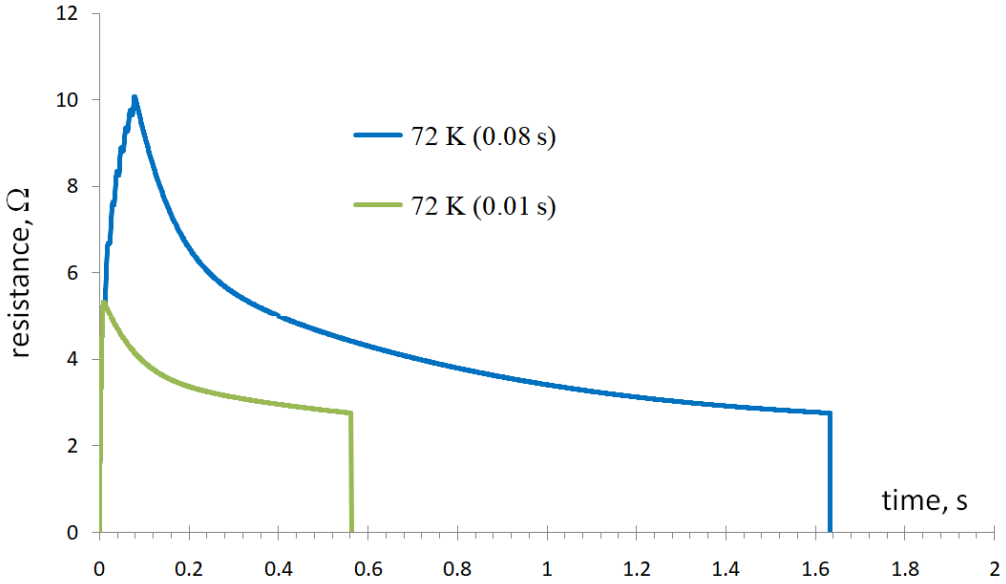


Figure 18. Changes of the HTS tape resistance of the limiter during short-circuit (0–0.08 s) and cooling down "72 K (0.08 s)" and during short-circuit (0–0.01 s) and cooling down "72 K (0.1 s)" for the initial temperature of the limiter before short-circuit = 72 K.

Table 9. Maximum resistance R_{max} of the limiter during short-circuit limitation and time of HTS tape recovery from the resistive state to the superconducting state $t_{R\text{-}N}$ (after the short-circuit ends) acc. Figure 18. T_0—initial temperature, t_{zw}—short-circuit duration.

Short-Circuit	T_0	t_{zw}	R_{max}	$t_{R\text{-}N}$
72 K (0.01 s)	72 K	0.01 s	5.33 Ω	0.55 s
72 K (0.08 s)	72 K	0.08 s	10.08 Ω	1.55 s

The limiter operating in the 72 K (0.08 s) regime cannot be reconnected in the system after less than 1 s because it returns to the superconducting state only after 1.55 s. Connecting a superconducting limiter in a resistive state to the protection system will cause a rapid increase in the temperature of the limiter. The cooling time for the temperature = 72 K (from 81.7 K to 72 K) is 6300 s. With two cryocoolers, the time (6300 s) reduces to 3240 s.

6. SFCL Compared with HTS Transformer

The SFCL is not the only superconducting device capable of limiting short-circuit current. I was a participant in the projects about HTS transformers. The studies [15–17] are 3 of 9 articles (with my participation) about HTS transformers.

The HTS transformer with the possibility of limiting short-circuits uses other cables, not SF types, without copper, but SCS type cables, with copper. Thus, upon transition from the superconducting to resistive state, the transformer cable has much lower resistivity than the HTS cable used in SFCL. Thus, the HTS transformer limits the short-circuit current to a lesser extent. Generally, the HTS transformer for short-circuit limitation is a very effective (in my opinion). However, it is a different device, constructed differently, that is more difficult to model numerically. In SFCL, the HTS tape characteristics are assumed to be a function of current and temperature. In the case of an HTS transformer, the magnetic field cannot be ignored, so the characteristics of the HTS tape are a function of three variables: current, magnetic field and temperature. In addition to this problem, there are other big problems: when switching from a low voltage to medium voltage, the weight of the device

(HTS transformer) increases tremendously. Additionally, the costs of the device are also so high that in small laboratories it is practically impossible to implement the HTS transformer project for the medium and high voltage networks.

Therefore, compared to the HTS transformer, the SFCL limiter is very light, not complicated and very cheap (compared to the HTS transformer, of course).

7. Conclusions

- Changing the concept of the limiter's operation from a superconducting fault current limiter (SFCL) to a superconducting surge current limiter (SSCL) is appropriate and has no disadvantages.
- This article describes how to change the SFCL limiter to SSCL by changing the current limiting operation time only. The SSCL ends when the limited short-circuit current passes through zero for the first time, i.e., after 0.01 s for a frequency of 50 Hz. Therefore, it can be applied to any already constructed SFCL limiter.
- In the case of building a new SSCL limiter, the design of the limiter can be slightly changed, but it will be described in a new article.
- The SSCL (Figure 17) should start working at 300% of the rated current. After the first limiting, 300% decreases to 231%. Additionally, now the power engineers can make the decision, or they agree to 231% and, during operation, the cryocooler will be restored to 300% after 1500 s, or the limiter is replaced with another limiter and it will resume operation after 1500 s.
- All the data presented show that this new concept must be adhered to.
- Another decisive piece of information is the use of the cryocooler to cool the limiter. Contact cooling with the use of a cryocooler is the only possibility of cooling the limiter in electric power applications.
- The possibility of changing the operating temperature allows for adjusting the parameters of the limiter to the electric power system needs.
- If somebody builds a limiter in a laboratory and its parameters do not match the assumption, then by changing the temperature, they can obtain the assumed parameters of the limiter.
- The manufacturer of many SFCLs (or SSCL) can build one type of limiter, and by changing the operating temperature, each can be adapted to the needs of the power industry.

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