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Tests and Analysis of a small-scale Noval Hybrid Type DC SFCL Prototype

Siyuan Liang, Yuejin Tang, Li Ren, Zhong Xia, Shuqiang Guo, Ying Xu, Zuoshuai Wang
State Key Laboratory of Advanced Electromagnetic Engineering and Technology,
Huazhong University of Science & Technology, Wuhan, China

Abstract—In recent years, high voltage DC power transmission is widely developed in the world. However, it is difficult for the existing DC breaker to cut off the fault transmission line with large short-circuit fault current. In a short-circuit fault of DC systems, short-circuit fault current is composed of initial transient impulse current and steady-state fault current. Therefore, a noval hybrid type DC SFCL is proposed with two-stage current limiting capability. In the early stage of short-circuit fault, initial transient impulse current is limited by inductance and resistance. In the later stage of short-circuit fault, a sustained and steady current limiting resistance is provided by the DC SFCL. A 220V/10A prototype of the DC-SFCL is developed and the parameter design of the DC SFCL prototype is presented. According to the experimental test and simulation analysis, the design scheme's effectiveness can be confirmed from high current-limiting ratio. Based on coherence of experiment and simulation, the current-limiting characteristics of the noval hybrid type DC SFCL can be well verified.

I. OPERATING PRINCIPLES AND EQUIVALENT CIRCUIT

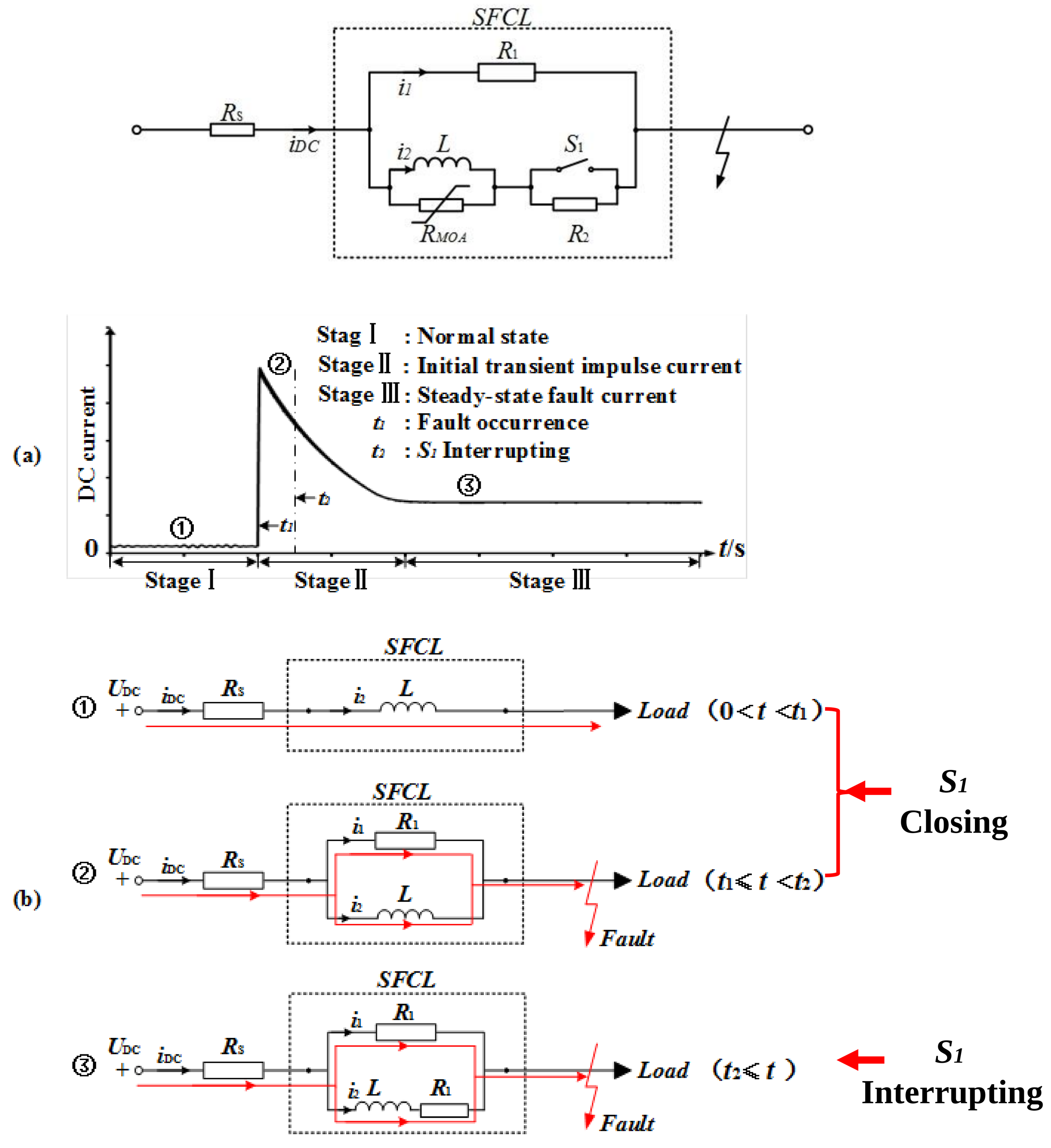
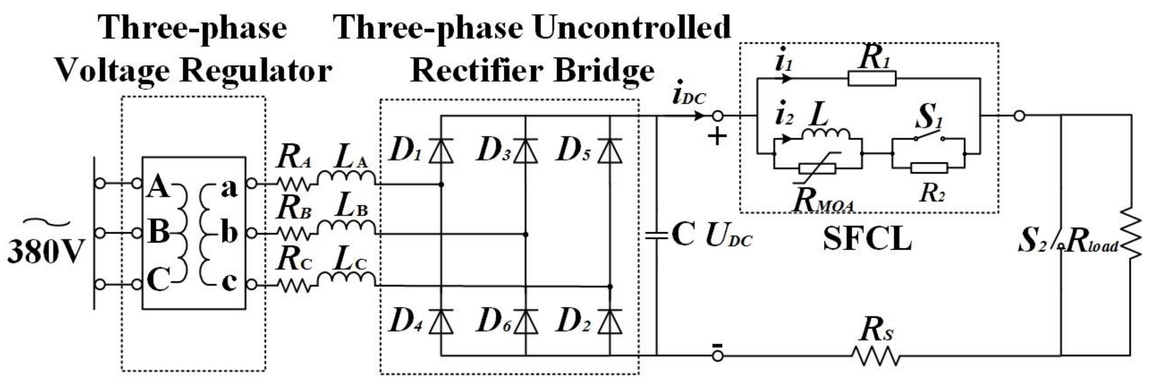
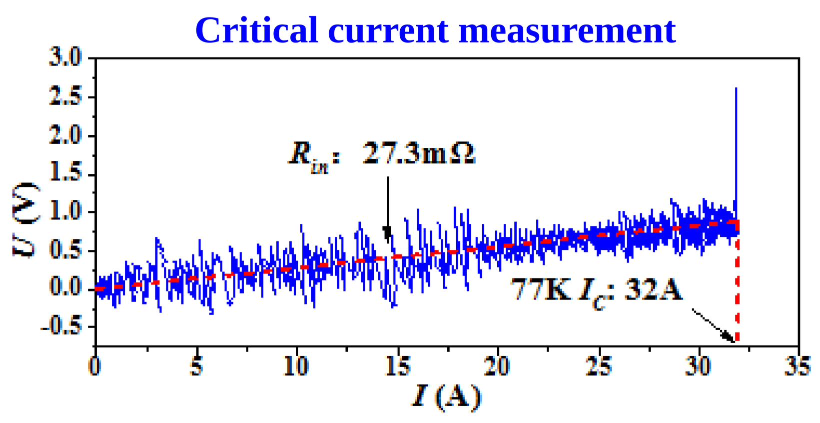


Fig. 1. (a) The characteristics of DC short-circuit fault current without any measures.
(b) Equivalent circuit diagrams of different operating stages in the noval DC SFCL.

II. SUPERCONDUCTING COILS AND DESIGN OF 220V DC SFCL PROTOTYPE





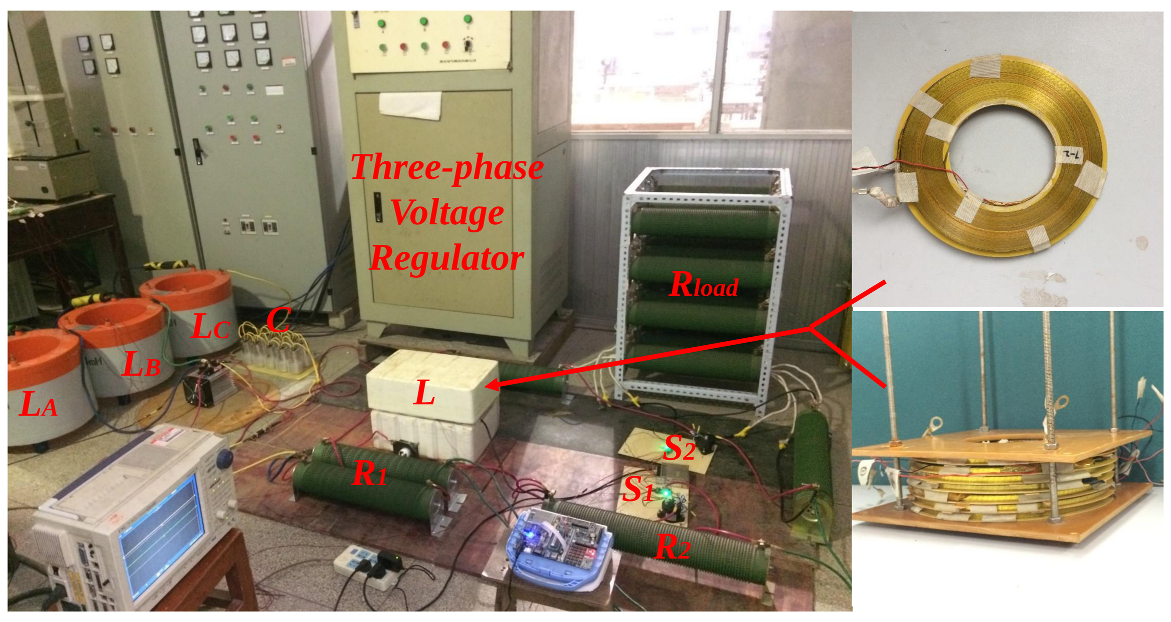


TABLE I
PARAMETERS OF SUPERCONDUCTING COILS

Parameter	Value
Superconducting tape	SuNAM4100
Material of type	GdBCO
Number of pancake coils	7
Turns of a pancake coil	114
Width of tape	4.05±0.02mm
Thickness of tape	0.12±0.01mm
Gap between two pancake coils	2.3mm
High of the whole coils, *h*	49.42mm
Outer radius, r_1	84mm
Inside radius, r_1	50mm
Internal resistance, R_{in}	27.3mΩ
77K critical current, I_C	32A

TABLE II
MAIN EXPERIMENTAL PARAMETERS

Parameter	Value
DC voltage, U_{DC}	220V
DC current, I_{DC}	10A
AC Inductance, L_A / L_B / L_C	33mH
Internal resistance of AC Inductance, R_A / R_B / R_C	665mΩ
Filter capacitor, *C*	697.2μF
Internal resistance of filter capacitor	18.2mΩ
Current limiting resistance, R_1	4Ω/6Ω/8Ω
Current limiting resistance, R_2	8Ω
Superconducting coils(77K), *L*	77.4mH
DC line resistance, R_S	2Ω
Load resistance, R_{Load}	20Ω
Time interval between S_1 and S_2, t_2-t_1	10ms/16ms/22ms

III. EXPERIMENTAL TEST AND SIMULATION ANALYSIS

A. Current limiting test

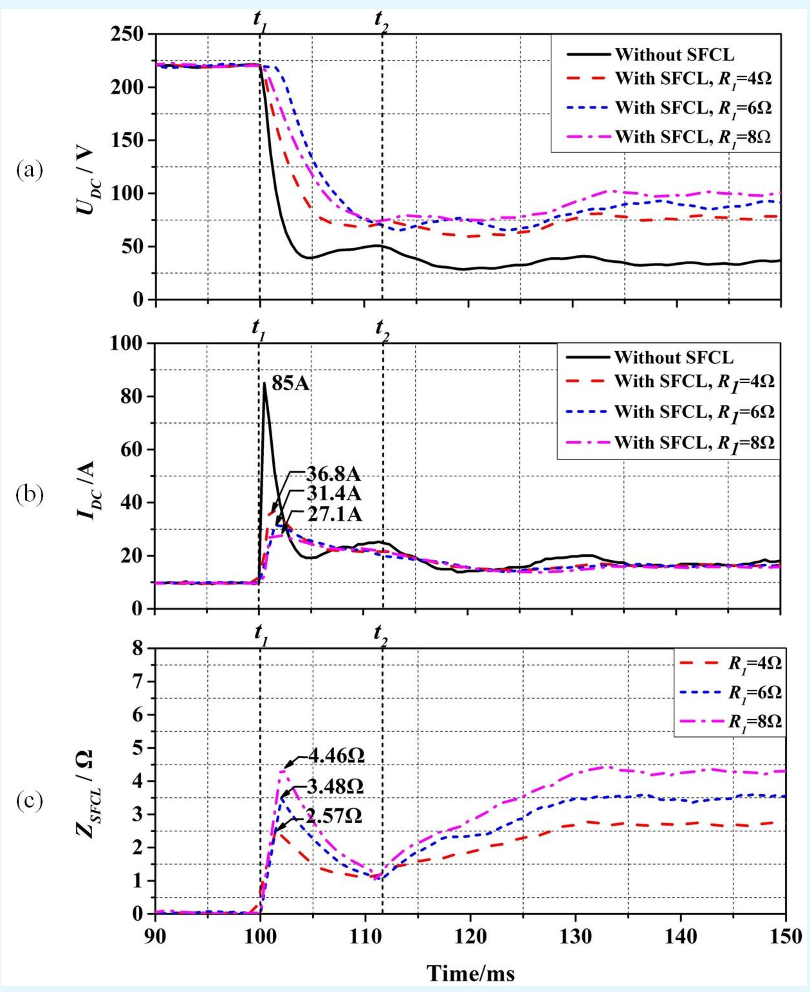


Fig. 2. Test result of the SFCL under t_2-t_1=10ms. (a) DC-side voltage U_{DC}. (b) DC current I_{DC}. (c) Equivalent current limiting impedance of the SFCL, Z_{SFCL}.

TABLE III
RESULT OF CURRENT LIMITING TEST

I_{Fault}	R_1	Z_{SFCL} Normal state value	Z_{SFCL} Transient peak value	Z_{SFCL} Steady value	Peak Value of I_{DC}	Rate of current limiting
85A	4Ω	0.027Ω	2.57Ω	2.67Ω	36.8A	56.7%
	6Ω		3.48Ω	3.43Ω	31.4A	63.1%
	8Ω		4.46Ω	4.16Ω	27.1A	68.1%

B. Impedance characteristics and Current transferring process of the DC SFCL

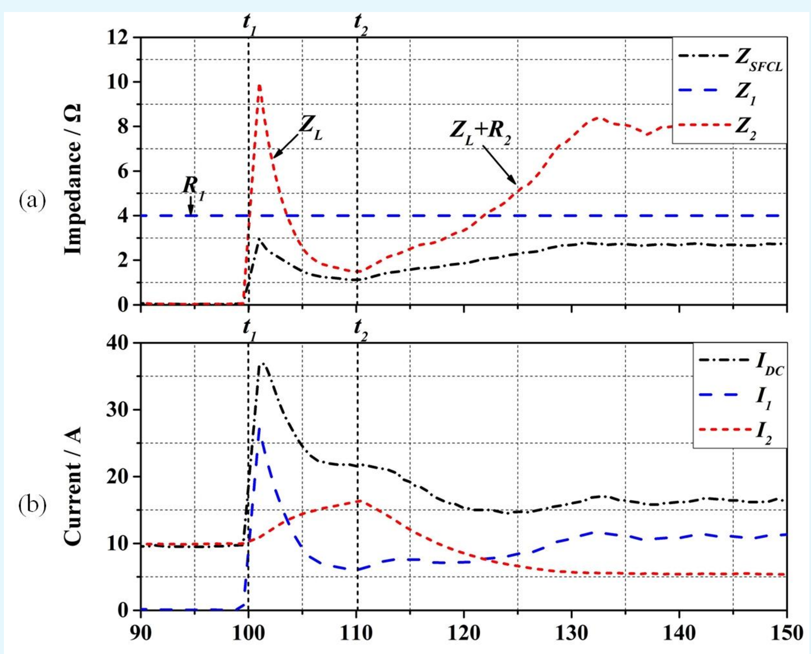


Fig. 3. When t_2-t_1=10ms and R_1=4Ω, test result of the SFCL. (a) Impedance variation characteristics of each branch. (b) Process of current transferring and distribution.

Z_{SFCL} is equivalent current limiting impedance of the SFCL, Z_1 is equivalent impedance of R_1 branch, where Z_1=R_1. Z_2 is equivalent impedance of *L* and R_2 branch, Z_L is transient equivalent impedance of inductance *L*, where

$$Z_2=\begin{cases}0 & (t<t_1)\\ Z_L & (t_1\le t<t_2)\\ Z_L+R_2 & (t_2\le t)\end{cases}$$

A mathematical relation between Z_{SFCL}, Z_1 and Z_2 is

$$Z_{SFCL}=Z_1\cdot Z_2/(Z_1+Z_2)$$

Therefore the changes of the overall current limiting impedance Z_{SFCL} and current transferring process depend on variation of Z_2. Accordingly, the operation modes of the DC SFCL can be regulated by Z_2 in order to deal with different situations.

C. Influence of S1 action speed on the DC SFCL

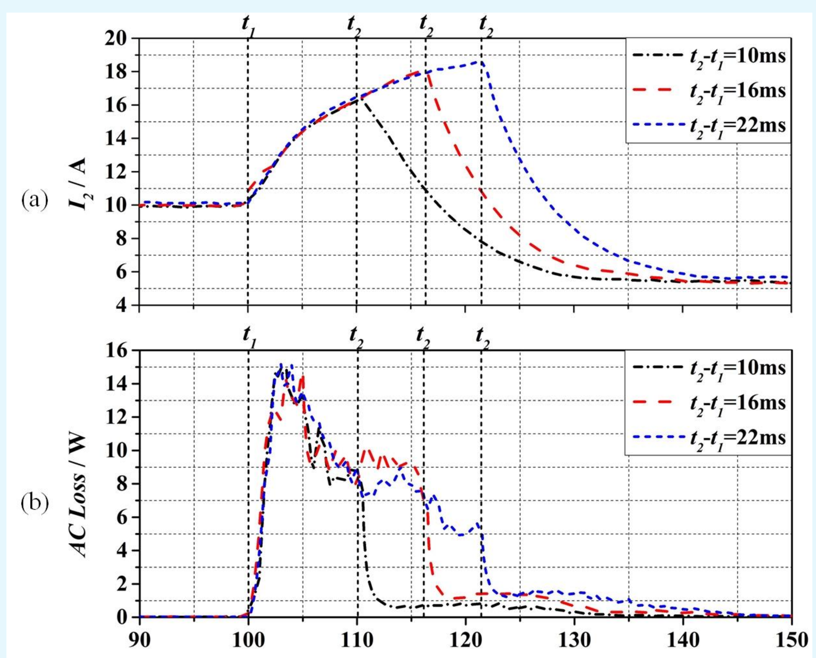


Fig. 4. When R_1=4Ω. (a) Test results of current I_2 with different delay time of S_1. (b) Corresponding calculation results of AC loss with different delay time of S_1 disconnection..

TABLE IV
TEST RESULT OF I_2 AND CACULATION OF AC LOSS

Delay time t_2-t_1	Peak value of I_2	Peak value of AC loss	Total loss from 100ms to 150ms
10ms	16.35A	14.9W	0.12J
16ms	18.04A	15.2W	0.18J
22ms	18.58A	14.7W	0.21J

In this test, R_1 is set to 4Ω and remains unchanged, delay time of S_1 disconnection after fault occurrence are respectively 10ms, 16ms and 22ms. The test results of current I_2 with different delay time are shown in Fig. 4(a). According to the test results of current I_2, corresponding AC loss of superconducting coils *L* are calculated by Kim-like model, shown in Fig. 4(b). The results are listed in Table IV.

D. Energy loss analysis of the DC SFCL prototyp

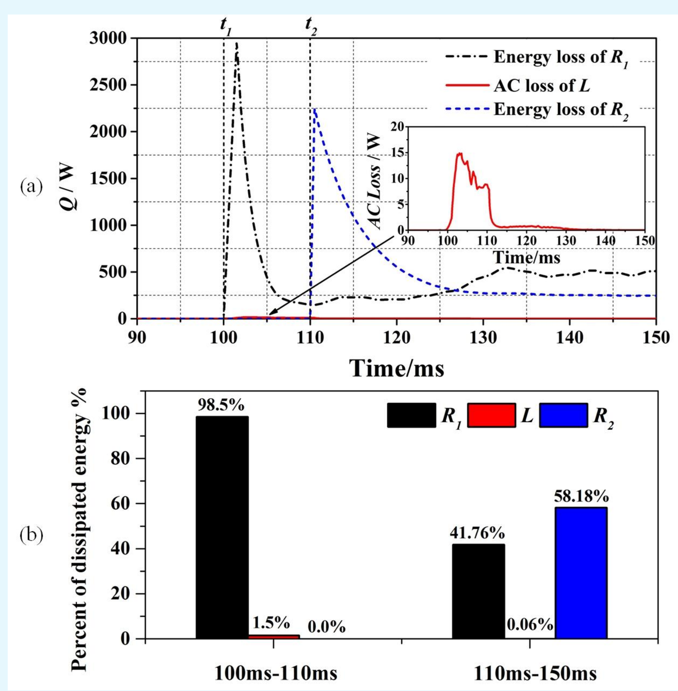


Fig. 5. When R_1=4Ω, t_2-t_1=10ms (a) Changes of energy loss in current limiting process. (b) Percentage of dissipated energy in the DC SFCL prototype at different time.

IV. CONCLUSION

(1) In normal state, total energy loss of the DC SFCL approaches zero and equivalent impedance is milliohm level, which usually is joint resistance.

(2) In current limiting process, equivalent impedance of the SFCL matches characteristics of DC short circuit current, with transient current limiting impedance and steady current limiting impedance. The SFCL can rapidly and effectively limit fault current with high rate of current limiting.

(3) AC loss of superconducting coils is very low. Most of energy from short circuit fault is absorbed and dissipated by R_1 and R_2, which ensures the safe and reliable operation of superconducting coils.