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DC SUPERCONDUCTING FAULT CURRENT LIMITER

Febin K Saju [1], Renukadevi S M[2]

[1] *Electrical Engineering Student, Musaliar College of Engineering and Technology Pathanamthitta,*

[2] *Associative Professor Musaliar College of Engineering and Technology Pathanamthitta, Kerala, India*

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Abstract: *A superconducting fault current limiter is a device that can limit fault current and ensure protection for the circuit. It Reduces the peak value of fault current, Improves the transient stability of the power system, Provides the system effective damping for low-frequency oscillations, and Causes no power loss in a steady-state condition. For ac application, there is an efficient SFCL are exists but for dc application, superconducting fault current limiter needs additional requirements than other systems. So, a new type of superconducting fault current limiter is proposed. The current transmission coil is connected to the dc transmission line and superconducting rings are placed in between the transmission line and iron core. During normal power transmission, magnetic flux coupling between the current transmission coil and iron core is prevented by the magnetic shielding of superconductor rings and the current limiting coil can effectively limit fault current. When the fault current reaches a certain level, the superconducting ring will quench and the shielding effect is greatly reduced. The coupling between the current limiting coil and the iron core gets strengthens, which increases the inductance. Thereby limiting the fault current*

Keywords: Fault current, Magnetic shielding, SFCL, Superconducting fault current limiter, saturable, Transient stability.

1. INTRODUCTION

Superconducting fault current limiters (SFCLs) utilize superconducting materials to limit the current directly or to supply a DC bias current that affects the level of magnetization of a saturable iron core [3]. While many FCL design concepts are being evaluated for commercial use, improvements in superconducting materials over the last 20 years have driven the technology to the forefront. Case in point, the discovery of high-temperature superconductivity (HTS) in 1986 drastically improved the potential for the economic operation of many superconducting devices. This improvement is due to the ability of HTS materials to operate at temperatures around 70K instead of near 4K, which is required by conventional superconductors. The advantage is that refrigeration overhead associated with operating at a higher temperature is about 20 times. Less costly in terms of both initial capital cost and operation
Superconducting Fault Current Limiter (SFCL) is a viable alternative to the use of conventional means of reducing fault current. Superconducting fault current limiter can reduce fault current within the first cycle of fault current and has zero impedance during normal operation and large impedance during fault condition which can limit fault current within a predefined value during an impedance into the circuit where it is connected. The SFCL does not only suppress fault current but also enhances the power system stability [5]. The limitation of component performance and topological structure of high-voltage direct current converter make it unable to resist short-circuit impact. The lack of a zero-crossing spot in DC fault current also makes it difficult for rapid malfunction cut off. Meanwhile, compared with the alternating current system, fault current increases rapidly and significantly in VSC-HVDC, posing high requirements on maximum cut off capacity and reaction speed of direct current breakers. The superconducting direct current limitation is a feasible solution for the above problems. DC power grid has different requirements on SFCL from AC power grid, SFCL should also be able to prevent the increase of fault current and sustained short-circuit current except rapid response, to achieve coordination between SFCL, direct current breakers, and currency converter. In the case of steady operation for the circuit, the SFCL cannot be influenced by excessively high electrical inductance. Hence, stable and low electrical inductance in normal operation, as well as current-limiting high electrical inductance are an ideal performance of current limiter. Magnetic shielding type SFCL, which reacts fast and converts low inductance to high inductance when short circuit fault occurs, can be able to achieve these target

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2. SUPERCONDUCTING FCL

The current limiting characteristics [1] of SFCL depend on its nonlinear response to temperature (T), magnetic field (B), and current density (J) as shown in Fig. 1.

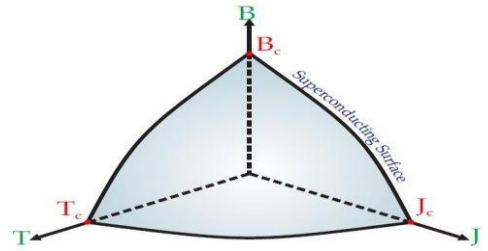

Fig-1. T-B-J Characteristics of Superconductor Material

The superconductivity of a superconductor material will be destroyed when the superconducting material is exposed beyond a certain temperature, magnetic field, and current density called critical values. Below these critical values, it has negligible resistance and this implies that it is in its superconducting mode, and above these critical values it has high resistance and it is the current limiting state. Therefore, increasing any of these three parameters beyond their critical limit will cause the conducting material to lose its superconducting property. The SFCL uses its variable resistance.

Superconductor fault current limiter does not suppress the fault current completely but rather reduces the fault current to a level that the equipment or devices can withstand. An SFCL helps to manage economically this fault current to avoid damages.

3. Types of superconducting fault current limiters

Superconductor fault current limiters are classified into two major types: Resistive-type SFCL and Inductive-type SFCL

3.1 Resistive-type SFCL(R-SFCL)

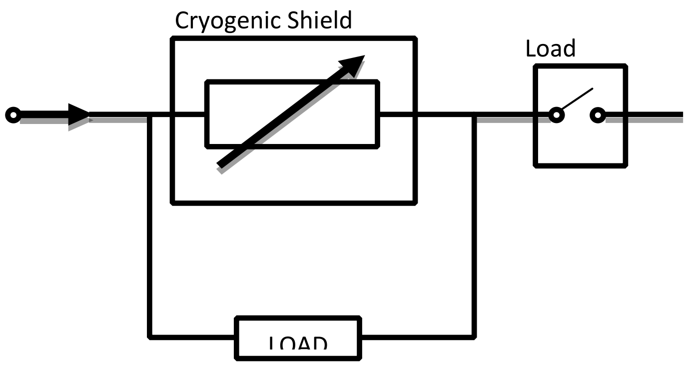

Fig-2 Structure of R SFCL

In resistive SFCL the superconductor is connected in series with the network to be protected. Under the normal operating condition, the R-SFCL[4] is in its superconducting state and passes the normal current without any losses. If the current increases beyond the critical current due to the occurrence of a fault, the superconducting material transits to a conducting state

and introduces a resistance in series to reduce the fault current. A resistor is connected in parallel with the superconducting material to avoid hot spots during quenching, to adjust the limiting current, and avoid over-voltage due to the fault current limitations. The main advantage of R-SFCL lies in its simple design, compact size, and lightness when compared with the Inductive-Type **SFCL.**

3.2 Inductive-type SFCL

Inductive SFCL's are mainly used in the application of the dc power system[4]. The inductive SFCL's are of two types: closed core inductive-type SFCL and open core inductive type SFCL

3.2.1 Open core inductive type SFCL

It is a special transformer connected in series with the network to be protected. This transformer has a conventional primary coil (copper winding) and a special secondary winding made of an HTS ring. Under the normal operating condition, the HTS ring prevents magnetic flux from penetrating the iron core; hence, the SFCL exhibits low impedance. During fault when the current increases above the critical current, the HTS ring quenches, the secondary now becomes resistive and so the inductance of the device rises. In this case, the SFCL represents high impedance.

The advantage of I-SFCL over R-SFCL is that the cryogenic power load is lesser because no heat ingress is caused through current leads into the superconductor.

Its disadvantages include significant losses, larger size, and high weight. So, this kind of SFCLs are not efficient for the application

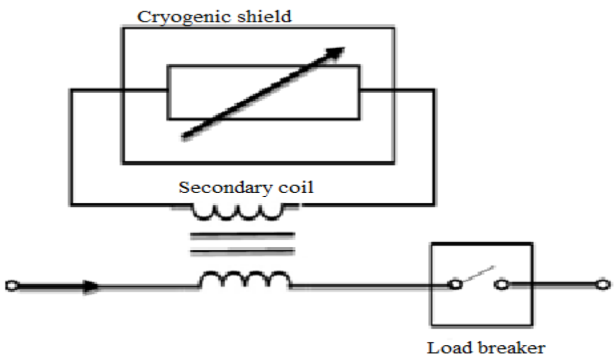

Fig-3. Structure of I-SFCL

4. CLOSED CORE INDUCTIVE TYPE SFCL

The closed core inductive-type SFCL [7] has more efficiency than the open core inductive-type SFCL. The closed core I-SFCL can limit the fault current in the first half cycle of the short circuit itself. On the normal operating condition, the superconductor rings don't allow the iron core to couple with the current transmission coil which is placed in the transmission line. But when the fault occurs within one second itself the superconductor ring quenches and iron core couple with the current transmission coil and inductance will be produced and fault current gets reduced.

The variation of permeability and resistance work together to affect the impedance of the transmission coil. In the ac power system, there is the zero-crossing point in the transmission current, the permeability of the iron core will spontaneously increase and reach saturation without the superconductor rings. The variation of permeability has no positive effect on current limiting, only the variation of resistance in superconductor rings plays role in fault current limiting. Therefore, compared with the ac power system, the SFCL can embody a larger current limiting impedance in the dc power system, which leads to a better limiting effect. Through changing the number of superconductor rings and the number of turns of one ring, the quenching threshold value can also be set with relevant line fault protection strategies. This process does not exist in the application in the ac power system. As a result, the magnetic shielding type SFCL is more suitable for the dc power system.

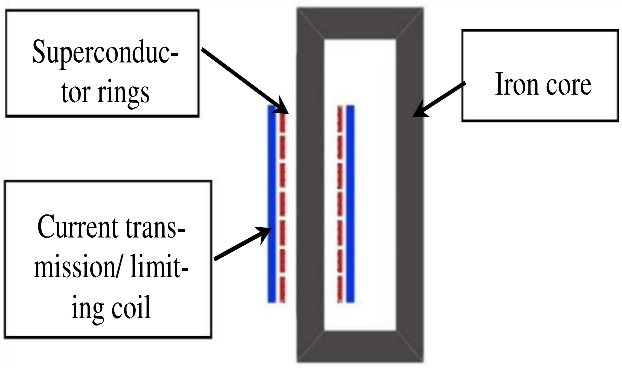

Fig-4. Closed Core Inductive type SFCL.

The principle of current magnetic shielding type SFCL in ac power system is changing the shielding effect through the quench of superconductor rings to increase the current limiting inductance. In the dc system, there is an additional current limiting principle by using dc magnetic shielding type SFCL the closed core inductive superconducting fault current limiter is the most efficient fault current limiter for the dc application.

5. MAGNETIC PERMEABILITY CURVE OF IRON CORE

The principle of current magnetic shielding type SFCL[7] in ac power system is changing the shielding effect through the quench of superconductor rings to increase the current limiting inductance. In the dc system, there is an additional current limiting principle by using dc magnetic shielding type SFCL

When current transmission/ limiting inductance, the coil is flux coupling with an iron core, the high magnetic conductivity of iron core can enhance inductance of the coil. when the dc rated current is in operation, the iron core is almost saturated, when the fault occurs, the iron core coil has no obvious advantages in enhancing the inductance compare with the air core coil. However, in the case of adding superconductor rings, the shielding effect can allow the iron core to remain in a low magnetization state at the beginning, as shown in H corresponding to rated current'. After the short circuit fault occurs, the permeability of the iron core will increase to the maximum value and then be reduced until the iron core reaches saturation. A high permeability will lead to a large inductance of the coil, which can improve the current limiting effect. Besides, the superconductor rings can be seen as a short-circuited secondary side of the coaxial transformer

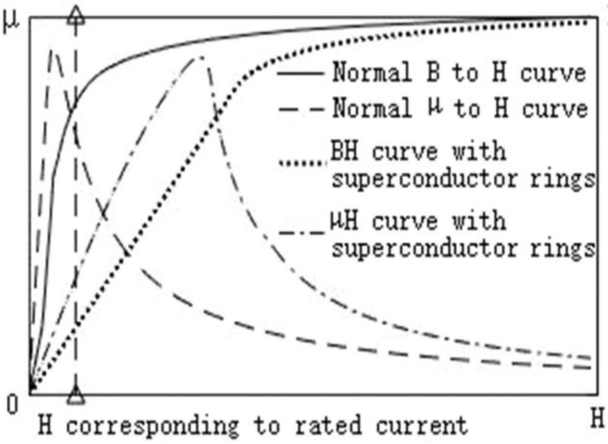

Fig-5. Magnetic permeability curve of an iron core, "μ" is magnetic permeability, "B" is magnetic flux density, "H" is magnetic field intensity.

When the superconductor rings quench after the short circuit fault, the superconductor rings will embody resistance, which may partly improve the current limiting effect. In the dc power system, the variation of permeability and resistance work together to affect the impedance of the transmission/limiting coil. In the ac powers System, there is a zero-crossing point in the transmission current, the permeability of the iron core will spontaneously increase and reach saturation without the superconductor rings. The variation of permeability has no positive effect on current limiting, only the variation of resistance in superconductor rings plays role in fault current limiting. Therefore, compared with the ac power system, the SFCL can embody a larger current limiting impedance in the dc power system, which leads to a better limiting effect. Through changing the number of superconductor rings and the number of turns of one ring, the quenching threshold value can also be set with relevant line fault protection strategies

6. EXPERIMENT AND ANALYSIS OF CLOSED CORE I-SFCL

For analysis of dc SFCL with the closed core [7] is done with two experiments they are performance test and current limiting test. The table below shows the parameters of components that are used for both tests.

Table.1 Parameters used in the experiment

components	**Parameter**	**specification**
Superconductor	One ring height	12mm
	Inner diameter of rings	112mm
	One ring turn	2
	Number of rings	20
Current transmitting/limiting coil	Coil height	292mm
	Inner diameter of coil	128mm
	The coil turs	60
Iron core	Diameter of core column	48mm
	Core window width	129mm
	Core window height	474mm
	Yoke height	45mm

There are twenty superconductor rings. Each superconductor ring is made of double-pancake shaped coils with the Bi2223 first generation of superconducting wires. Rings are wrapped on a supporting barrel. There are twenty card slots to fixate each ring. Sixty turns of current transmission/limiting coil are also manufactured by Bi2223 superconducting wires. The wire is 4 mm wide and 0.22 mm thick and is calibrated with a critical current of 180 A in self-fields. The critical current of superconductor rings and Current transmission/ limiting coil is tested about 160 A. Iron core is made of silicon steel sheets with high magnetic permeability (reach to 7000~10000 H/m). The cryogenic container is an epoxy resin bucket. The non-metal container is used to avoid interruption in the experiment. Basic parameters of the prototype are shown in Table. 1

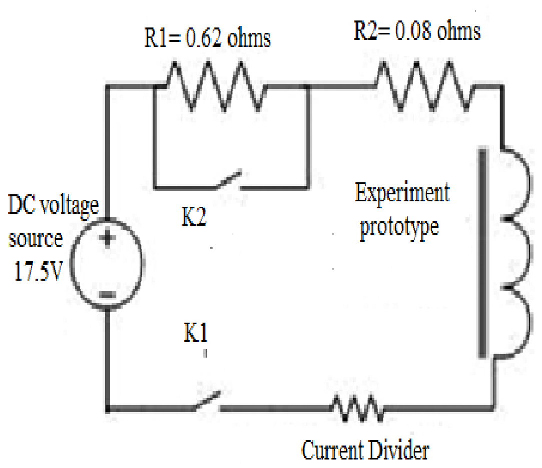

Fig -6. Current limiting tests circuit.

6.1Performance test

The performance tests[7] of the SFCL prototype are conducted with a 200 A DC impulse current. Air core coil has fixed inductance of 0.16 mH, 0.12 mH, 0.08 mH, 0.05 mH with 0, 6, 12, 20 superconductor rings

The inductance of the iron core coil varies with the current variation of the current transmission/limiting coil. The measured inductances of the current transmission/limiting coil in different conditions. It indicates that inductance decreases when the number of superconductor rings increases. The shielding effect enhances more with the increase of superconductor rings. The current corresponding to the maximum inductance increases with the increase of the superconductor ring.

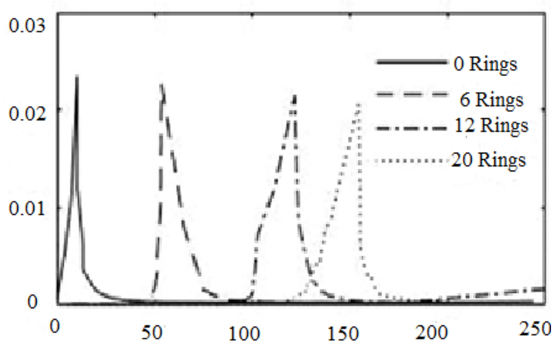

Fig-7*:* The inductance of current transmission/limiting coil

6.2Current Limiting Tests

The R1 will be shortly connected[7] at the time of 5 ms after the limiting tests begin. The cunt changes from 25 A to 220 A in the test without a prototype. Impulse current test is conducted to the prototype. Electric current and voltage of current transmission/ limiting coil are recorded. Due to the non-linear performance of the iron core, the electrical inductance of the current transmission/ limiting inductance coil also indicates non-linear changes. The equation of electrical inductance and voltage $u=L*di/dt$ is used to calculate the inductance of the current transmission/ limiting coil. The calculated inductance is the average inductance from the beginning of the short circuit to the calculating time point with the increase of superconductor rings

Table -2: Current limiting test results

N	L0	LE	L1	LE	L2	LE
0	0.16	29.70%	0.389	45.85%	0.028	1.40%
6	0.12	24%	0.832	61.00%	0.802	31.30%
12	0.08	16.20%	0.247	34.70%	0.91	32.70%
20	0.06	0.112%	0.065	0.131%	0.204	0.098%

In the table above, “N” is the number of superconductor rings; “L0” is the 10 ms inductance of the test without iron core; “L1” is the 10 ms inductance of the test with the iron core; “L2” is the 25 ms inductance of the test with iron core. The inductances are calculated from 5 ms when the limiting tests begin. LE is the limiting effect.

At 10 ms the current limiting effect of the prototype with 6 superconductor rings is the strongest, and have the biggest inductance; at 25 ms the current limiting effect of the prototype with 6 superconductor rings and 12 superconductor rings is almost identical, and prototype inductance with 12 superconductor rings is biggest. Because of the shielding effect, at the beginning of the short circuit, the effect of current limiting with superconductor rings is poorer than without ring, but the current limiting effect will suddenly increase, which is because the superconductor rings' remaining the iron core in low magnetization state and the inductance of current transmission coil will increase rapidly after short circuit. The time of current limiting effect conversion can be defined as the response time of the DC SFCL which is no more than 1 ms. A superconducting fault current limiter (SFCL) is potentially an attractive candidate for this application and satisfies most of the requirements [7] . SFCL's can operate naturally and quickly to prevent an increase in the fault current, limiting the DC fault current to more acceptable levels. Superconducting materials are ideal for DC networks since there are no losses for pure DC making them virtually invisible to the system when operating normally.[7] The application of SFCLs for HVDC systems has received very limited attention though

7. SIMULATION OF ±160 KV HVDC SYSTEM

The Nan' ao Island ±160 kV MMC-HVDC system of China Southern Power Grid Company as a reference [7], the simulation system is constructed. This system is a four-terminal DC system with a rated current of 1 kA. The bipolar fault is the most serious short-circuit fault, which is used to simulate and verify the feasibility of DC SFCL. If there is no current limiting measure, the current rises sharply after a short circuit, which exceeds the blocking current, and the DC system will be blocked. Besides, the short circuit current will rise to a very high level of 22 kA, which will bring great pressure to the circuit breaker. In the Nan' ao Island ±160 kV MMC-HVDC system, to prevent blockage of the DC system, short circuit current should not exceed 3 times rated current within 2 ms. Installation of a 500 mH inductor will greatly slow down the current rise rate, will not exceed three times the rated current of 3 kA, and the short-circuit current is also greatly limited. But in the normal operation of the HVDC system, adding such a large inductance may cause second-order oscillation with the circuit capacitance, which will affect the operation of power system.

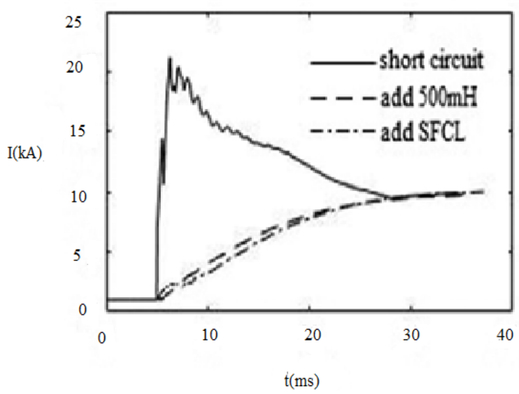

Fig -8. Bipolar fault current of the ±160 kV HVDC system. (a)Without current limiting measure. (b) Add the DC SFCL

A DC SFCL matching the HVDC system is designed and the basic parameters of the SFCL are shown in Table 6.1. Both the superconductor rings and current transmission/ limiting coil are manufactured by superconducting wire. The superconductor rings should be manufactured by the second generation of superconducting wires so that there is large resistance after the quench. Air core inductance of current transmission/ limiting coil is only 14.3 mH. In normal operation the inductance of the current transmission coil only about 10 mH, with the shielding effect of superconductor rings. This DC SFCL can achieve the same current limiting effect as 500 mH inductance when installed in the HVDC system. And the response time of the DC SFCL is not more than 1 ms.

8. COMPARISON OF AC SFCL AND DC SFCL

8.1 AC SFCL

Figure 9. shows the AC SFCL response to the short circuit current in the ac microgrid [3]. The dotted line indicates the current response with SFCL and the broad line represents the current response without SFCL Here shows the fluctuation of the broad line shows the fault current reaches or short-circuit occurs

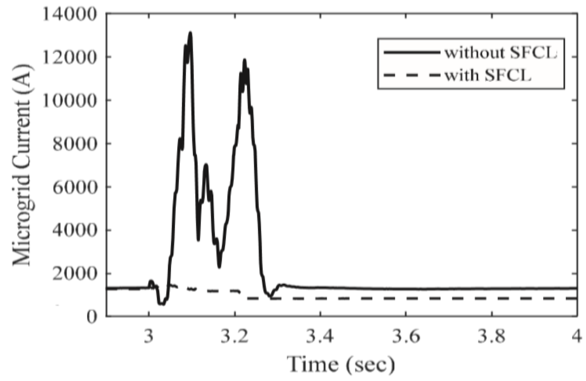

Fig -9. AC SFCL response to short circuit current in ac microgrid

From the figure, it is clear that without any time lapse the SFCL reduces the fault current and only the rated current is allowing to flow through the load. So, considering the efficiency of ac SFCL is less high or the occurrence of fault current and SFCL reaction time is less than 1ms.

8.2 DC SFCL

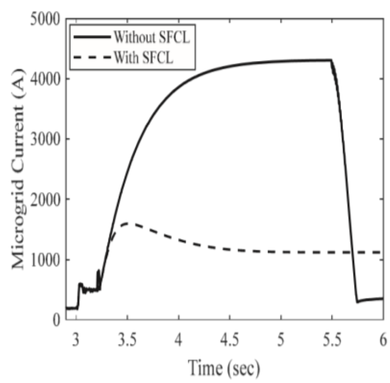

Fig -10. DC SFCL response to short circuit current in dc microgrid

Fig.10 shows the DC SFCL response to short circuit current in ac microgrid [3]. The dotted line indicates the current response with SFCL and the broad line represents the current response without SFCL. So here shows the fluctuation of the broad line shows the fault current reaches or short-circuit occurs. Here it is clear that even the first half cycle of the fault currents the SFCL limits the current to rated current but when compared to AC SFCL it is not as such faster or the time taken for fault occurs and the response of SFCL is about 2ms.

9. CONCLUSION

Based on the experimental data and simulation, and comparison we can come to several summaries In the HVDC system, the closed core I-SFCL is more suitable because it can limit fault current within the first half cycle of the short circuit. The time gap between the fault occurs and the SFCL responses are less than 1s. So as a fault current limiter in the dc system, the closed core I-SFCL is convenient. And closed core I-SFCL is more efficient than the open circuit I-SFCL because closed core I-SFCL can reduce the fault current more efficiently. But when compared with AC SFCL the efficiency of closed core I-SFCL is less which is about 1ms.

The closed core inductive type superconducting fault current limiter can give a quick response to the fault current compare with the open core I-SFCL. It is a long-lasting and low maintenance cost. In this type of SFCL, the cryogenic power load is lesser compare with the ac SFCL's because in ac SFCL the superconductors are directly placed on the transmission line itself so to reduce the heating effect of being under critical temperature the cryogenic power is more needed for ac SFCL's. And the dc SFCL has higher efficiency compared with the open core I-SFCL, even in the first half cycle of the short circuit can limit the fault current. Which is less than 1s. For the dc application, the most convenient FCL is the closed core inductive type superconducting fault current limiter.

The DC SFCL can display low inductance in normal operation and high inductance when a short circuit occurs. The shielding effect of superconductor rings makes the iron core in the low magnetized state in normal operation when a short circuit fault occurs maximum permeability of iron core will be used and the current limiting inductance will be very large, which only works in DC systems, not in AC system. The simulation in the ±160 kV HVDC system verifies the feasibility of the new type DC SFCL.

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