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Transition mechanism of an Inductive-resistive Superconducting Fault Current Limiter (IR-SFCL)

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Abstract. Superconducting fault current limiters (SFCL) are protective devices that limit the current in power lines when it suddenly increases above a certain safe level as a consequence of a fault. This element is connected in series with the line and has a null impedance when the line current is below the safe value (limit current) but significative increase the impedance when the line current tries to surpass this value. The variance of impedance is only due to the internal state of superconductors, without the participation of any mechanical element. Obviously, there are not any similar elements manufactured with conventional technology.

There are two basic types of SFCL: those that present a resistive impedance (R-SFCL) after transition, and those which present an inductive impedance (I-SFCL). The authors are working on an SFCL concept that includes both mechanisms operating interactively.

In this work, the combined transition mechanism is explained, the prototype under study is presented, and some theoretical and experimental results are shown.

Key words. Superconductor, Fault current limiter, SFCL

1. Introduction

Fault currents pose significant risks to power systems. They are sudden and excessive increases in electrical current due to short-circuits or other anomalies, and can lead to equipment damage, power outages, and safety hazards. Traditional protection devices may not react swiftly enough to effectively mitigate these surges. Superconducting fault current limiters have emerged as a promising solution, leveraging the unique properties of superconductors to limit fault currents rapidly and efficiently.

Superconductors are materials that, when they are cooled below a certain *critical temperature* T_c, exhibit two inseparable properties: total absence of electrical resistance (perfect conductivity) and total expulsion of the magnetic field (perfect diamagnetism). However, when exposed to currents exceeding their *critical current* I_c or external magnetic fields beyond certain threshold called *critical magnetic field* H_c or B_c, they transition to a normal resistive state through a process known as *quenching*. This transition can be harnessed to suddenly introduce an impedance into a circuit when it is necessary, for example, when the current increases during a fault. In this way, A superconducting device goes unnoticed when the operating current is normal (the rated current, e.g.), but when the current rises dangerously, its state changes to resistive, limiting it.

Numerous references to the fundamentals of superconductivity can be found in the literature. (see, e.g., [1-3]).

2. Basic SFCLs

Although several configurations of SFCL can be found [4-5], there are two basic types which depend on the type of impedance they impose under a fault: Resistive SFCL (R-SFCL) and Inductive SFCL (I-SFCL). Both are connected in series with the line to be protected, and both are transparent as long as the current in the line does not exceed a preset maximum safety value I_{max}. When this happens, the superconductor integrated in the device changes to its normal state (resistive and paramagnetic) and make the limiter to show an impedance that it didn't have before.
The mechanism in each case is as follows:

A. Resistive SFCL

Resistive SFCLs consist of a superconducting element directly connected in series with the power line (Fig. 1).

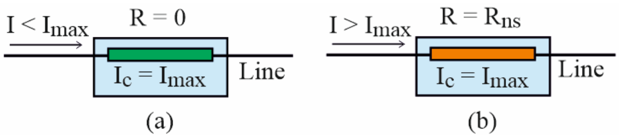

Fig. 1. Operation of the R-SFCL

The element is designed so that its critical current I_c coincides with the maximum current allowed on the line I_{max} Under normal operating conditions ($I_{line} < I_c$), the superconductor allows current to flow without resistance. When a fault occurs and the current exceeds the safety limit of the line $I_c = I_{max}$, the superconductor quenches, and rapidly transitions to the normal state (resistive state) and the element exhibits an impedance:

$$Z = R_{ns} \tag{1}$$

Obviously, this sudden increase in resistance reduces the fault current.

B. Inductive SFCL

On the other hand, I-SFCLs, typically consist of an excitation coil (preferable superconducting, i.e., $R = 0$) connected in series with the power line. The excitation coil has a ferromagnetic core separated of it by a superconducting magnetic screen (see Fig. 2).

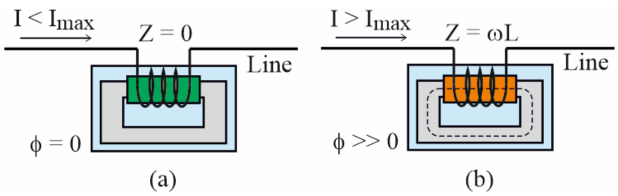

Fig. 2. Operation of the I-SFCL

The device is designed so that when the current I in the line is less than the preset safety current I_{max}, the magnetic field created on the screen is less than its critical magnetic field B_c and therefore, the diamagnetism of the superconducting screen prevents the magnetic core from being magnetized (Fig. 2a). The element does not present any impedance to the line.
But if the line current exceeds the maximum allowable I_{max}, The magnetic field it creates around the screen exceeds its critical value B_c. Then, the screen transitions to the normal state (paramagnetic), the magnetic shield disappears, and the core becomes magnetized (Fig. 2b). The magnetic flux ϕ makes the element to suddenly interpose an impedance on the line:

$$Z = \omega L = 2\pi f \frac{N^2 \mu_{Fe} S_{Fe}}{l_{Fe}}, \tag{2}$$

where f is the frequency (50 Hz, usually), μ_{Fe} is the permeability of the magnetic core, N is the number of turns of the coil, and S_{Fe} and l_{Fe} are the mean cross section and the mean length of the magnetic flux path respectively.

C. Comparison between basic technologies

R-SFCLs have advantages over inductive ones in terms of design simplicity: they are smaller and lighter than the latter. They also offer a faster response, acting even on the first cycle of the fault current. This is related to the direct interaction of the superconductor state with the fault current. On the other hand, the transition by current is not homogeneous and the heat generated during quenching in the regions where first occurs, endanger the integrity of the superconductor. They overheat during a fault and need time to cool before returning to service. In extreme situations, they can be destroyed due to inhomogeneous quenches, as it first occurs at specific points in the material (called hot spots) that may not withstand the currents.

I-SFCLs have the advantage that the superconducting element is not directly exposed to the line current, potentially reducing thermal and electrical stresses. However, they are bulkier than resistive ones due to the magnetic components.

3. Proposal of a new hybrid SFCL

In order to eliminate the problem of inhomogeneity transition of R-SFCLs, the authors have proposed a new hybrid configuration consisting of a resistive stage and an inductive stage connected in series.

A. Concept

As said above, the problem with R-SFCL is that the transition is produced by current, that is, when the line current exceeds the critical current of the superconductor I_c, and this is not completely homogeneous throughout the material. A solution may be to make the R-SFCL transition by exposing it to a high magnetic field, greater than B_c, before the current reaches its critical value I_c.
For this purpose, the appropriately calculated magnetic field that appears after the transition in the core of an I-SFCL can be used.
Fig. 3 shows the concept. The resistive stage of this *Inductive-resistive* SFCL (IR-SFCL) is located in an air gap made in the magnetic core of the inductive stage.

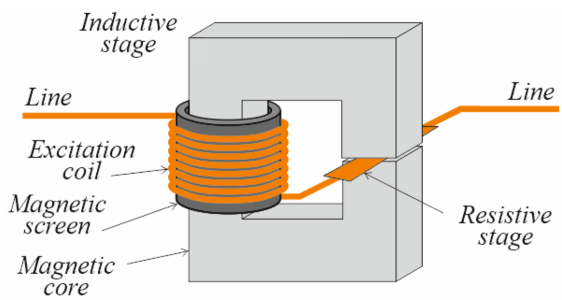

Fig. 3. Concept of operation of the IR-SFCL

The coil of the inductive stage is sized to make transit the screen with $I_{max} < I_c$, before the resistive stage transitions by current.
On the other hand, the magnetic circuit is calculated so that the magnetic field in the air gap, after the inductive stage transition, is greater than the critical magnetic field of the resistive stage B_c. So, when the inductive stage transitions, the resistive stage is fully immersed in a magnetic field greater than its critical magnetic field, and therefore it also transitions, but now it does so homogeneously.

B. The first proposed IR-SFCL

A first prototype based on the concept described above was built and tested in the laboratory. As seen in Fig. 4, this IR-SFCL was designed with an EI type magnetic core with slightly shorter side limbs to form the air gaps in which to house the resistive part.
The excitation coil and the resistive stage were made with the same continuous (no joints) superconducting

commercial tape from SuperPower Inc. [6], which is a tape of 130 A of critical current.
The screens were initially commercial bulk cylinders from Can Superconductor [7], but thy are brittle and expensive. For this reason, we decided to build our own screens using superconducting tape [8].

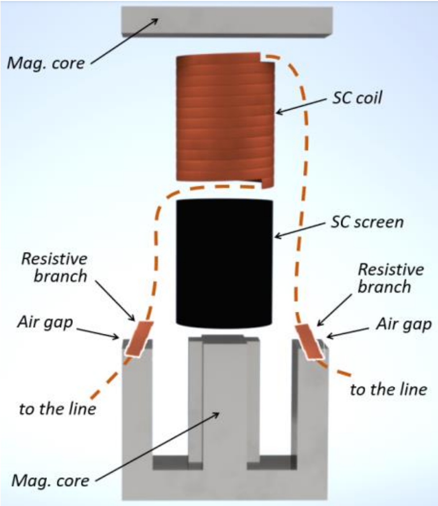

Fig. 4. Structure of the first prototype of I-R SFCL built and test by the authors

The laboratory tests shown in Figs. 5 and 6 were carried out with the first prototype described.

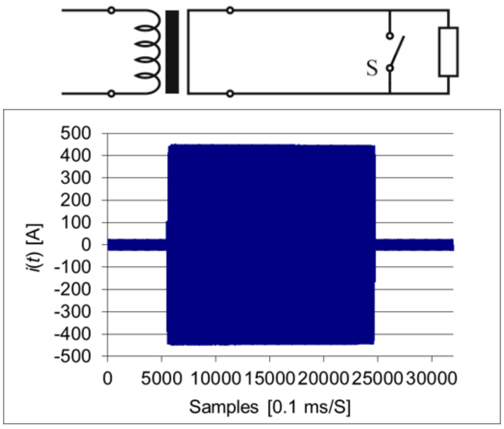

Fig. 5. Short circuit test at 50 Hz without IR-SFCL. *S* is set to ON after 0.5 s and is set to OFF 2 s later.

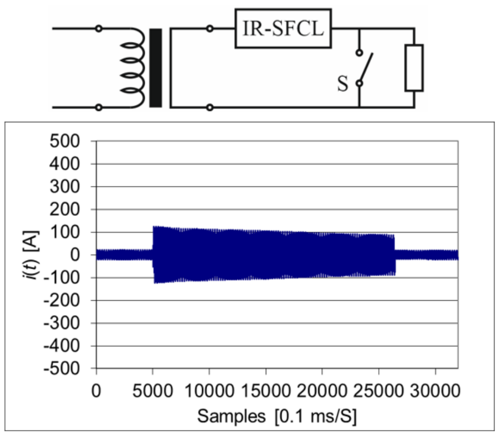

Fig. 5. Short circuit test at 50 Hz without IR-SFCL. *S* is set to ON after 0.5 s and is set to OFF 2 s later.

The test circuit consists of a 1000 A toroidal transformer that supplies a load that demands 20 A-peak. A switch *S* in parallel with the load causes a shortcircuit in the source for 2 s. The short-circuit current without limiter reaches 450 A-peak in that period (Fig. 5), but with the IR-SFCL connected, it only slightly exceeds 100 A-peak (Fig. 6).
Regarding the value of the impedance after the transition, this consists of the resistance of the resistive stage (1) in series with the reactance of the inductive stage (2). that is to say:

$$Z = \sqrt{{R_{ns}}^2 + (\omega L)^2} \quad (3)$$

Although the overall results were very good, the study of the limiting capacity of each stage separately showed that during the short circuit, practically all of the IR-SFCL's impedance was provided by the inductive stage. The small contribution of the resistive part was due to the short length of the superconductor subjected to the magnetic field (very short air gaps).

This situation led to discarding the previous geometry and searching for a new geometry that allows a long length of superconducting tape to be accommodated within the magnetic field. These considerations led to the IR-SFCL proposal which is currently under study.

4. The IR-SFCL under study

The inductive-resistive SFCL designed by the authors integrates resistive and inductive elements to take advantage of their respective strengths and mitigate their weaknesses. As in the previous prototype, the device consists of two stages (resistive and inductive) connected in series, as sketched in Fig. 6. The inductive stage is located on the four poles of a ferromagnetic structure like that of a synchronous machine. The differences are that there are superconducting magnetic screens between the coils and the poles, and the entire device is static.

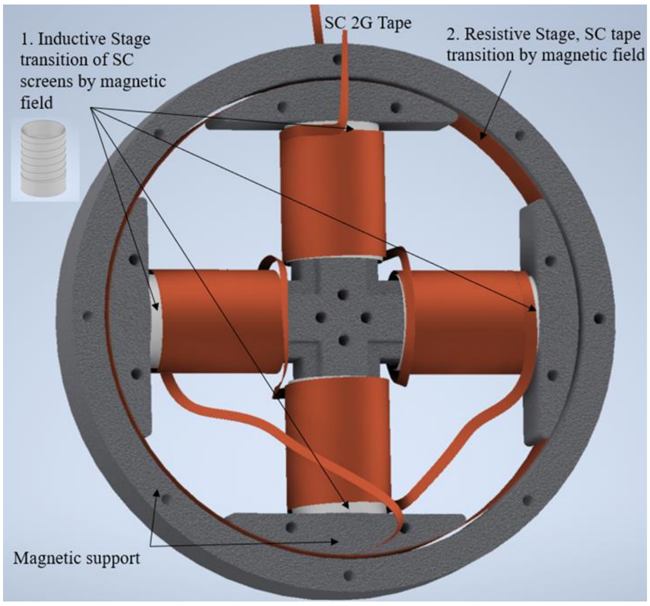

Fig. 6. Structure of the final proposed IR-SFCL

The resistive stage consists of a superconducting tape placed on the air gap between the poles and the inner face of the external ring. This allows the length of the tape under the magnetic field to be increased by increasing the number of turns under the ring.
Under normal conditions the superconducting screen exhibits perfect diamagnetism, effectively shielding the magnetic core from the magnetic field generated by the line current. The resistive stage works with a current lower than the critical current and without an external magnetic field; so, it presents null resistance.
This results in a negligible impedance of the entire device.
When the line current exceeds a predetermined threshold (I_{max}), the superconducting screen transitions to its normal state, allowing the magnetic field to penetrate the core from the poles, crossing the air gap to the outer ring. The magnetization of the core causes two effects:
On the one hand, it increases the inductive reactance, thereby establishing a first limitation on the fault current.
On the other hand, the magnetic field in the air gap increases above the critical value of the resistive stage located there, causing it to also transit and establishing the second limitation to the fault current.

5. Real prototype

Fig. 7 shows a real image of the prototype built by authors. All the connections are made with the same superconducting tape using to build the coils and the resistive stage. The unit is located into the cryostat where it will be tested at a temperature of 77K, submerged in liquid nitrogen.
The external connections are made with braided cable with a section 10 times larger than that of the superconducting tape.

6. Advantages of the IR-SFCL

By combining both inductive and resistive elements, the main weaknesses noted in section 2C can be compensated: the inductive stage can be lightened, since a significant part of the protection impedance is provided by the resistive part, while the resistive stage is protected from inhomogeneous quenches that can damage the material.
Other advantages of the proposed configuration are:

1) *Enhanced Current Limitation:* The dual mechanism provides a more substantial impedance increase during faults, effectively reducing fault currents to safer levels.
2) *Improved Reliability:* The device's design must ensure that even if one stage fails, the other can still provide a good degree of protection.
3) *Reduced Thermal Stress:* The initial inductive response limits the rate of current rise, potentially reducing the thermal stress on the resistive stage and prolonging its lifespan.
4) *Minimal Impact on Normal Operations:* Under standard conditions, the SFCL presents negligible impedance, ensuring that regular power system operations are unaffected.

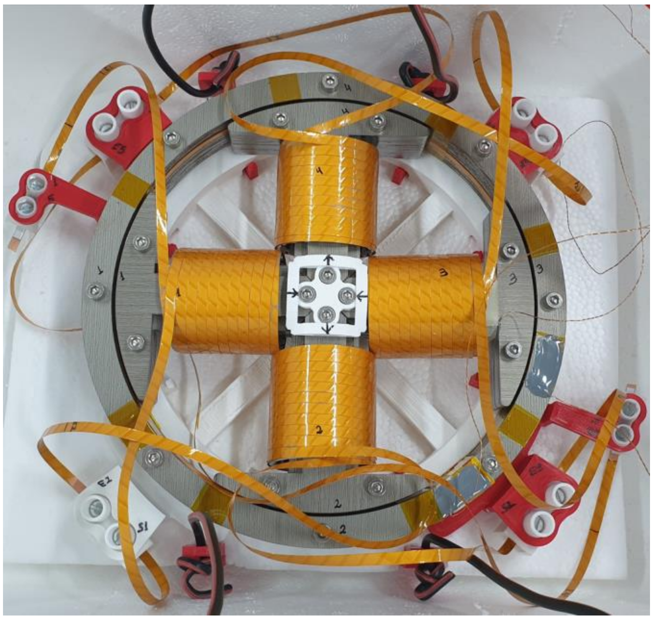

Fig. 7 Image of the IR-SFCL prototype built in the “Benito Mahedero” laboratory of Electrical Applications of Superconductors.

7. Conclusion

The inductive-resistive superconducting fault current limiter proposed by authors. represents a significant advancement in power system protection technology. By synergistically combining the principles of both resistive and inductive SFCLs, this device offers a robust, reliable, and efficient solution to managing fault currents.

It worth notices that now the transition of the resistive stage is produced by a sudden excess of magnetic field, resulting in a homogeneous transition unlike the current transition mentioned above.

References

[1] RG Sharma, Superconductivity: Basics and applications to magnets, Springer Nature, (2021)
[2] VZ Kresin, SA Wolf, Fundamentals of superconductivity, Springer Science & Business Media. (1990)
[3] M Tinkham,. Introduction to superconductivity. Courier Corporation, (2004).
[4] M. Noe, M. Steurer, “High-temperature superconductor fault current limiters: concepts, applications, and development status”, Supercond. Sci. Technol., (2007)
[5] A. Morandi, “State of the art of superconducting fault current limiters and their application to the electric power system”, Phys. C: Supercond., 484 (2013), pp. 242-247
[5] G Didier, G., Bonnard, C.H., Lubin, T.: Comparison between inductive and resistive SFCL in terms of current limitation and power system transient stability. Electr. Power Syst. Res., (2015), 125, pp. 150–158.
[6] https://www.superpower-inc.com/Technology.aspx
[7] https://www.can-superconductors.com/hts-bulks-and-materials/bi-2223-magnetic-shields/
[8] A. Álvarez, B. Rivera, B. Pérez and P. Suárez, "Study of Magnetic Shielding of Ferromagnetic Cores, with Solenoidal HTS Tape Screens, for SFCL Applications," IEEE Access, (2025), vol. 13, pp. 37649-37655