Design of a SFCL with an Inductive Stage in Series with a Resistive Stage Which Transits by Magnetic Field

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Abstract. One of the most interesting applications of superconductors in power systems is the so called "Superconductor Fault Current Limiter (SFCL)". This is a device that makes the lines exhibit a variable short-circuit impedance: very low (almost null) under normal operation, and high when the current increases above the security limit of the line. There are two types of SFCL: resistive and inductive. The first one consists of a superconducting element in series with the line. The element is designed with a critical current equal the security limit of the line. When the current in the line is higher, the element transits and a high resistance arises, protecting the line. The second type is connected in series with the line too. It consists of an inductor with the magnetic core shielded by a superconducting screen. The screen is designed to transit by magnetic field when the current in the coil (line current) is higher than the security limit of the line. At this time, a high reactance arises protecting the line. The PhD thesis we are working on is a new concept of SFCL with two stages (resistive and inductive) in series designed to solve some problems of each type separately. In this case, the resistive stage is located in the gap of the inductive stage magnetic core. Firstly, the objective is to make the magnetic screen transit. When this happens, the magnetic field penetrates the core and surrounds the resistive stage provoking its transition. In this paper, we present the work philosophy of this novel device, which does not have equivalent in conventional (non-superconducting) technology.

Keywords: Superconductivity, Fault current limiter, Magnetic transition

1 Introduction

The superconducting fault current limiter (SFCL) is a device that detects the increase in the current above a certain value, (for which it is designed) and inserts in the network a high impedance that does not exist under normal conditions.

This variation of impedance in the network allows it to work in normal conditions with a low short-circuit impedance, with the consequent performance in terms of quality of supply and stability. In fault conditions this impedance increases, reducing the current and therefor the switchgear size and cost.

SFCLs are reliable devices, with low environmental impact and easily adapt to power systems based on alternative energies, which makes them very attractive from a technological point of view and, under the right conditions, economically.

One of the most important challenges in electrical switchgear, is the fault current limiter, which has a clear application in two increasingly common situations: the demand for larger capacity in distribution networks and the inclusion in these of the distributed generation systems (DGS).

In the first case, increasing the capacity of the lines raises the value of the short-circuit currents above the capacity of the protection devices. Currently, there is no suitable solution to this problem.

The second case is the inclusion of distributed generation systems in the distribution networks, especially when it comes to renewable energy (wind turbines, photovoltaic panels, fuel cells, etc.) that needs connection systems to network based on power electronics.

For some years, especially since the appearance of high temperature superconductors (HTS) in 1987, research on the application of these materials to fault current limiters have been carried out.

A superconductor is a material that below a certain temperature (*critical* temperature*, Tc)* has zero electrical resistance and perfect diamagnetism, as long as the current it carries is not higher than a certain value (*critical current, Ic*) and is not held to a field magnetic higher than one given (*critical field, Bc*). That is, the superconducting material will retain its properties as long as the conditions of temperature, current density and magnetic field described are maintained below its critical values.

When the current exceeds this value, the material loses those properties, behaving as a resistive medium with permeability practically equal to that of air. This situation means that the material has moved from superconducting state to normal state.

For electrical application, the most interesting superconductors are the so called "high temperature superconductors". They work at temperatures higher than the liquefaction temperature of Nitrogen (77K; -196 °C), its nature (usually ceramic), makes its Resistivity is high, which is a good feature for the purposes of current limitation.

Due to these characteristics and its design, a SFCL could lead to benefits not only in the protection, but in the quality of the output voltage in normal operation as no impedance is interposed at the protection point.

In summary, this system that gives the line characteristics of impedance adaptable to the current, so that when the current limit is exceeded, it presents an impedance that it did not have in normal operation, it is not necessary to size the rest of the protections to the impedance of normal regime.

2 Contribution to Life Improvement

The main issue in this research is relevant due to the impact that this type of device can have on DGS, to which sustainability seems to lead in Electrical Engineering. The initial hypotheses are:

a) The SFCL increases the impedance of the short-circuit on the line that protects when its activation value is exceeded, this allows it to show very low impedance under normal operating conditions, improving the quality of the power supplied.

b) SFCL allows to expand the capacity of the lines without changing the size of the protections. It is intended to quantify this possibility under different scenarios.

c) SFCL operation is totally physical (a thermodynamic change of state) and therefore, environmentally free of impact.

3 State of the Art

The exhaustive study of the configurations of the SFCLs, their operating principles, characteristics, advantages and disadvantages have been carried out by several authors [1-2] who have delved into some interesting structures in terms of operating principles, commercial possibilities and their integration in DGS.

Recent studies [3] offer a review and analysis of the different types of existing SFCLs. These studies are divided into three groups: Quench-type SFCLs, Non-quench-type SFCLs and Composite-type SFCLs. The typologies associated with the prototype presented here classified as Quench-type SFCLs and is constructed by combining two of them.

Regarding the present work, the main typologies of interest are the resistive and inductive type. Inductive SFCLs use the magnetic field of a low impedance coil, connected in series with the line to be protected. The core of the coil is shielded by a superconducting screen. The loss of superconducting properties on the screen results on a magnetization of the core and sudden increase of the impedance in the coil. The SFCL is designed to lose the screen superconducting properties when the magnetic field created by the line current exceeds the protection value [4-5].

The resistive type uses the resistance of superconducting circuit connected in series with the line. When the circuit is in superconducting state no resistance is shown in the line. If the current in the line exceeds the protection value, the superconductor transits to normal state and inserts a high resistance in the line. The circuit is designed so that the maximum allowed current is the HTS critical current [6]. There are some applications of this SFCL typologies to real cases. [7-8].

Both types have advantages and disadvantages [9]. In the resistive typology, problems of non-uniform heating and hot spots may occur [2,10]. The problems are controlled as several research activities, using different HTS materials, are carried out. In fact, several successful prototypes have been installed in medium-voltage distribution systems [11-12]. The inductive typology has the disadvantage of weight gain due to the core and recovery times somewhat higher than the resistive type [3]. Both need cryogenic systems that are currently very reliable but increase the cost of these devices.

Nevertheless, other studies propose solutions by using technologies which combine both typologies, as in the case of the present work [13].

It is also interesting to mention the publications that analyze their optimal location in DGSs [14] and the benefits that imply their use in these networks [15].

Finally, in terms of basic design criteria, other documents, analyze topics such as the criteria for the selection of superconducting tapes [16], the analysis of their degradation [17-18], studies for the improvement of the combined performance of impedances [19], thermal stress analysis [20], and loss analysis in HTS coils [5].

4 Proposed Model

4.1 Background of the Work Presented

The inductive-resistive SFCL is an original proposal of the "Benito Mahedero" Group of EAS designed to prevent the destruction of a resistive SFCL non-uniform heating conditions (hot-spots) [13]. In this proposal, a resistive SFCL is forced to transit by applying an external magnetic field greater than the critical magnetic field, just before the current transition. The magnetic field is created by a magnetic-shield iron-core-type inductive SFCL, sized to lose the magnetic shield just before the current reaches the critical current in the resistive SFCL. Connecting these elements in series, we take the advantage of an impedance reinforcement by including the inductance of the inductive SFCL after the transition. The prototype studied consisted of a ferromagnetic core with two air gaps, as shown in Fig. 1.

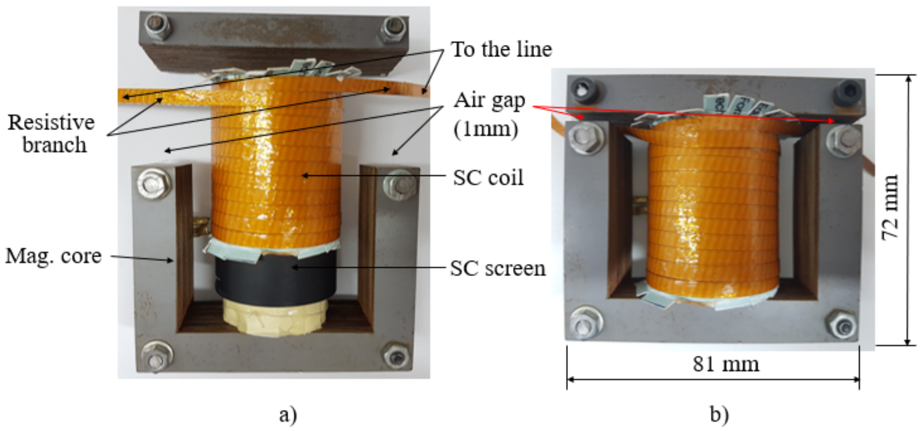

Fig. 1. SFCL prototype image developed by the "Benito Mahedero" group. a) Prototype deployed. b) Assembled prototype.

The inductive stage was made from HTS BSCO tape wound on a superconducting cylinder that shields a ferromagnetic core.

When the line current flowing through the coil exceeds the permitted limit, the magnetic field generated exceeds the cylinder critical magnetic field and the shielding disappears. Then the current in the coil establishes a high magnetic field in the core, affecting the HTS in the resistance stage.

The resistive stage consists of two sections of superconducting material in series with the line and the inductive element (in fact, they are extensions of the BSCO tape coil ends, avoiding joins). They are located in two 1 mm air gaps in the magnetic core of the inductive stage, as shown in Fig. 1. The transition to normal state of this section occurs after the transition of the inductive stage, by magnetic field and not by current as usual in conventional resistive SFCLs, avoiding the problems arising from current transitions. This is possible due to the correct sizing of the device, known the critical values of the screen and the tape so as the characteristics of the core.

4.2 Test and Results of the First Prototype

The prototype described above was tested in a simulated line consisting in a 15 A(rms) source feeding the rated load Z_L. Fig. 2 shows the set-up of the line with no protection. A switch *S* in parallel to the load permits to short-circuit the load. The current in the line was measured by a Hall probe connected to a DAQ where the waveform was recorded at a sample rate of 10 kS/s.

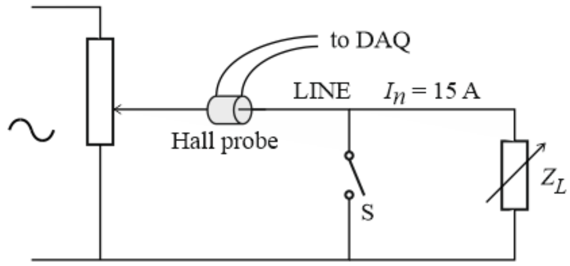

Fig. 2. Test circuit with no protection in the line.

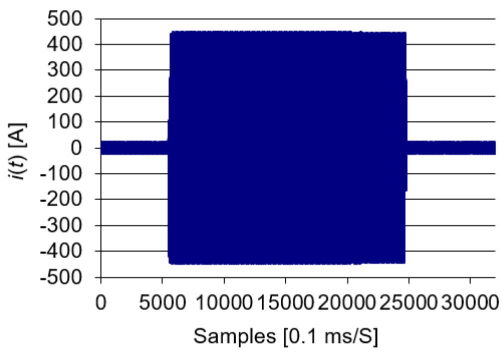

Fig. 3. Current in the unprotected line during the test. After connection, the line works at rated conditions during 0.5 s. Then a short-circuit of 2 s is held.

The result of this test is shown in Fig. 3. The *rms* value of the short-circuit current was 318 A, corresponding to a short-circuit impedance of about 4.7 %.

The measurements were repeated with the same source configuration and time sequence, but with the SFCL connected to the line as shown in Fig. 4.

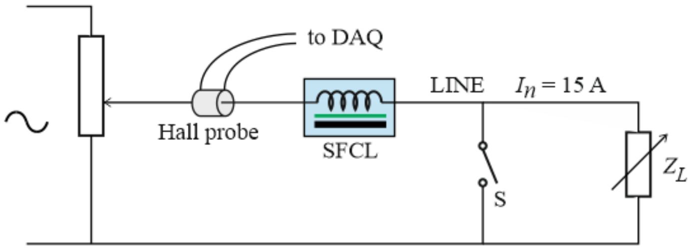

Fig. 4. Test circuit with the SFCL in the line.

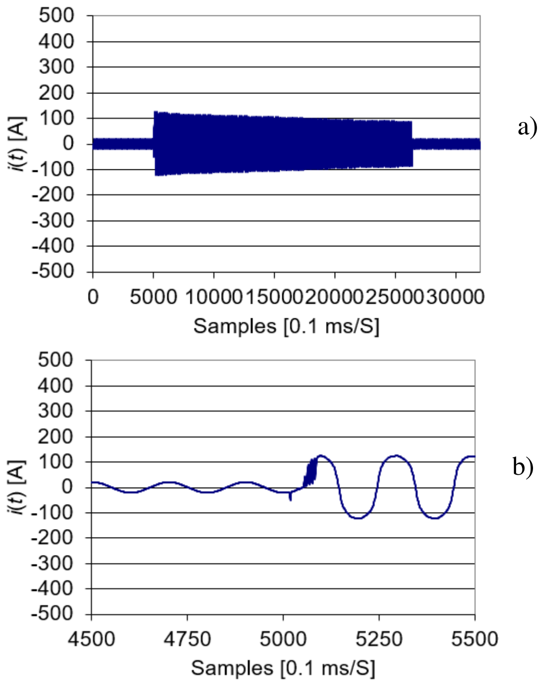

Fig. 5. Current in the line protected with the SFCL during the test. After connection, the line works at rated conditions during 0.5 s. Then a short-circuit of 2 s occurs. a) Full sampling. b) Waveform detail when the short-circuit occurs.

Fig. 5 shows the results of this test. Before the short-circuit event, the rated current passes through the line just as in the previous test. That means that the SFCL is *transparent* to the current and the short-circuit impedance remains at 4.7%. However, the short-circuit, after 0.5 s, is initially reduced to 88 A(rms). That means that the short-circuit impedance (line + SFCL) has increased to a value of almost 17%, which is better for protection. And, what is much better, this increase of the short-circuit impedance only occurs when the fault occurs, remaining at a lower value (better for stability) in normal operation.

As the short-circuit is present, a slow reduction of the peak value can be observed. This effect is under study, but the high value of the time constant suggests that it is probably a thermal effect.

The results of the described prototype were uneven in both stages: The inductive stage (tested independently) showed a 70% reduction in the short-circuit current. On the other hand, the reduction of the current in the resistive stage was practically null due to the short length of the resistive branches.

4.3 New Prototype Description

The structure proposed in this new design represents a drastic change with respect to the models previously studied. The modifications mainly affect the structure of the magnetic circuit, and the resistive stage of the combined SFCL.

The aim is to increase the length of the tape in the SFCL's resistive stage, whereby, the available air-gap must be increased. Thus, we propose a new magnetic support (Fig. 2) consisting of a cross-shaped central body with four polar expansions, surrounded by an external ferromagnetic shell, forming a structure similar to that of a synchronous machine (e.g., 4-pole machine, as in figure).

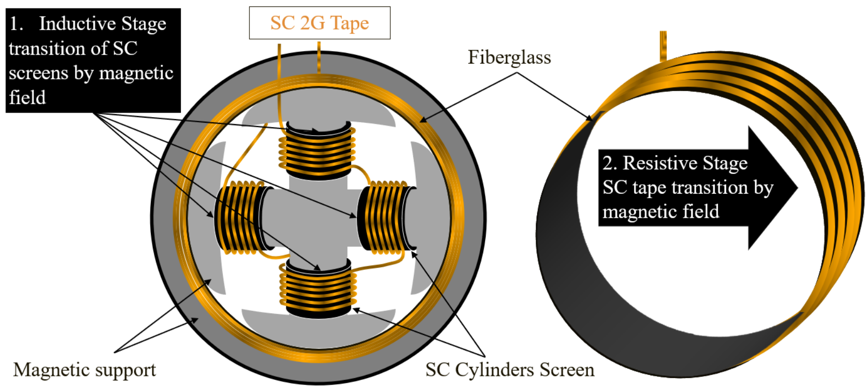

Fig. 6. Scheme of the SFCL prototype under study.

Surrounding the polar expansions (or poles), four superconducting cylinders will be inserted. Their mission is the same as in the previous prototype, i.e., to shield the pole from the magnetic field as soon as it is kept below the critical value.

The inductive stage coils are made by winding 2G HTS tape around the superconducting cylinders. The number of turns of the coils must be calculated again to ensure that the limit current (of the line to be protected), makes the superconducting cylinder to transit just before reaching the critical current in the belt.

When this happens, the poles and the air-gaps are magnetized, and the resistive stage tape is immersed in the magnetic field, which causes its transition to the normal state.

The winding direction of the coils must originate magnetic poles of opposite direction in contiguous poles.

These new modifications are expected to improve the operation of the inductive stage of the SFCL.

After finishing the winding of the SFCL's inductive stage, the arrangement continues to wind the resistive stage over a fiberglass support that surrounds the inner core and provides compactness to the application without modifying the magnetic properties or increasing its weight. As can be seen in Fig. 2, practically the entire cylindrical surface of the fiberglass support is under the influence of axial magnetic field, when it appears in the poles. This way, it is possible to increase the length of the tape in the resistive stage.

The final scheme of the prototype in Fig. 2, shows the terminals of the application that must be connected in series with the line to be protected.

Initially, while the intensity flowing through the line is kept below the limit value, the superconducting cylinders have a perfect diamagnetic behavior, and the ferromagnetic material does not detect the magnetic field. In this situation the impedance presented by the SFCL is negligible.

When the current in the line exceeds the limit, the superconducting screens transits to normal state, allowing the establishment of the magnetic field on the magnetic circuit with the following consequences:

1. A high inductive impedance in the coils, connected in series with the line.
2. The transition of the resistive stage to normal state, and the resulting resistive impedance connected in series with the line.

The effect that we expect as a result of these modifications is a great short-circuit current limitation capacity due to the increase in the total impedance presented by the SFCL, without the risks of damage to the HST tape.

5 Discussion of Results

The design and development proposed in the Research Project entail important technical and economic benefits. The inclusion of the prototypes under study in the current electric power system would reduce the rated value and the cost of the associated protection switchgear, since, for practical purposes, the short-circuit current of the lines that integrate them decreases considerably.

It would imply improvements in the efficiency of the network, an increase in the reliability of the supply for the users and a lower cost of the protection of the system as well as the improvement in the quality of the output voltage in normal operation, for the distribution companies.

From the point of view of the environmental impact, the cryogenic system needed for superconducting conditions, either by immersion in liquid nitrogen or by conduction in a vacuum chamber, is practically harmless with the medium in which it is installed, having no harmful effects of it.

In addition, other superconducting devices that take advantage of these cryogenic systems could be integrated, with possible consequences on the dimensions of the sections of lines, including the assigned voltages, which would affect the design of the transformation centers themselves.

The study that is proposed is, in that sense, bidirectional, that is, the inclusion of the limiters would lead to the optimization of the parameters of the electrical systems with DGS and the consequent resizing of them, and again, the situation would lead to the retrofitting of the SFCLs.

6 Conclusions and Further Work

The design of a new SFCL device is presented. The main objective is to solve some problems shown by the typologies presented before.

It is intended to define a reliable device with low environmental impact, easily adaptable within the distribution networks of distributed generation systems, especially when constituted from renewable energy.

The SFCL device not only aims to meet the protection requirements for which it is designed, but also focuses on improving the quality of service in normal operation, since it will not imply any impedance at the point of protection.

The current state of the investigation has already carried out an exhaustive review of the existing bibliography and a previous analysis of the losses in the different prototype elements. The possibility of replacing the Bulk-type cylindrical magnetic screens with others constructed with HTS tape is beginning to be studied. The first results obtained are promising.

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