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Design Aspects and Test of an Inductive Fault Current Limiter

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Abstract **– Magnetic shielding inductive fault current limiters with high temperature superconducting tapes are considered as emerging devices that provide technology for the advent of modern power grids. The development of such limiters requires magnetic iron cores and leads to several design challenges regarding the constitutive parts of the limiter, namely the primary and secondary windings. Preliminary tests in a laboratory scale prototype have been carried out considering an assembly designed for simplicity in which the optimization of the magnetic coupling between the primary and secondary was not the main focus. This work addresses the design configuration of an inductive current limiter prototype regarding the assembly of the primary and secondary windings in the core. The prototype is based on a closed magnetic core wound by a primary, built from a normal electric conductor, and a short-circuited secondary, built from first generation superconducting tape. Four different design configurations are considered. Through experimental tests, the performance of such prototype is discussed and compared, in terms of normal and fault operation regimes. The results show that all the configurations assure effective magnetic shielding at normal operation regime, however, at fault operation regime, there are differences among configurations.**

Keywords **– Fault current limiters; High-temperature superconductors; Power grids; Short-circuit currents.**

I. Introduction

Electric power equipment has to be designed to maintain modern power networks highly reliable and fail-safe in order to contribute to saving costs and operational optimization. It is common oversizing some electric power equipment in order to deal with faults such as short-circuit currents the values of which may highly exceed the nominal values. However, oversizing the majority of the electric power equipment tends to be very expensive that leads to becoming unfeasible. For these reasons, there are several current limiting devices that help to reduce the costs of investment on oversized power equipment. Nevertheless, it is not enough to limit the current. Features such as very rapid reaction, self-reset after a fault and minimal impact on the grid performance are other desired features [1], [2], [3] and [4].

Superconducting fault current limiters (SFCLs) are considered as emerging devices that provide technology for the advent of modern electricity networks and thus helping to mitigate several operation problems that such grids can experience as well as prevent the upgrade of the equipment [5] and [6].

Among all different topologies of SFCLs, the resistive is the one that has been most developed and subjected in many field tests, see e.g. [7], [8] and [9]. This topology uses a high temperature superconductor (HTS) material that is in series with the line circuit and uses the transition from the superconducting state to normal state to limit short circuit currents. The design is very compact; however the need for current results in losses even during normal operation. On the other hand, inductive SFCLs require an iron core which make them relatively heavy but do not need current leads, require lesser amounts of superconductor and are robust against hot-spot formation. A field test has carried out by ABB Company many years ago using HTS bulk cylinders [10], and only recently, due to the emergence of HTS tapes [11], [12], [13] and [14], several projects have been performed, either using first generation [15] or second generation tapes [16].

This work addresses the design issues of a magnetic shielding inductive SFCL prototype and presents experimental results of normal and fault current regimes in order to understand performance dissimilarities between the different assemblies that were carried out. These experiments are important in order to understand the design challenges that are involved and provide pertinent information for the development of a medium voltage device.

A. Research Question

The collected information of this work will contribute to answer the ongoing research question:

Taking into account modern power grids, based on dispersed, embedded or distributed generation, are inductive SFCLs attractive devices in terms of performance to protect such grids from short-circuit faults?

B. Motivation

The motivation behind this research lies on the recent developments of high quality HTS materials that can provide the development of several applications, such as SFCLs, without any counterpart on conventional electric power equipment, which might help to solve several problems that surge from the emergence of modern power grids [17].

The growing demand for energy provided from distributed generation, mostly from renewable energy sources, requires optimized, controlled and secure connections to electric transmission and distribution grids. Since most of distributed generators are under environmental phenomena dependency, their amount of generated energy is variable as function of time and environmental conditions, which means that such grids are inherent fault-susceptible due to unpredicted current flows [18]. For these reasons, fault current limiters are used to prevent short-circuit damages and avoid expensive upgrading of the grid.

Fault operation regimes, such as short-circuit currents, can compromise the security, reliability, and availability of the electric equipment present in the grid [19]. In order to avoid chaotic occurrences and provide reliability to energy delivery, contributing to the increased penetration of renewable energy sources in modern power grids, SFCLs have been found, see e.g. [7], [8] and [10] that have potential to perform an enhancement of energy management systems by assuming a collaborative behavior through the limitation of short-circuit currents that are the result of their awareness of fault operation regimes in the grid. The SFCLs offers very close characteristics to the ideal fault current limiter [5] and [20].

II. Prototype and Experimental Apparatus

Magnetic shielding SFCLs are based on the same principle of the transformer but with the secondary shorted. The magnetic core of the developed prototype is wound by a primary coil, built from a normal electric conductor, and a short-circuited secondary coil, built from the first generation superconducting tape. The primary is connected in series to the circuit under protection.

During normal operation regime, the short-circuited secondary shields magnetically the core ensuring negligible voltage drop at the terminals of the primary, since no magnetic flux flows in the magnetic core. When a fault occurs, the line current increases abruptly which induces high currents in the secondary and thus quenching the HTS material. As a consequence, the impedance of the primary coil increases due to the penetration of magnetic flux in the core. For these reasons, the limiter autonomously triggers itself. When the fault is suppressed, the limiter recovers its original state almost instantaneously [21] and [22].

Ideally, this device ensures negligible voltage drop at its terminals during normal operation regime and effective current limitation in fault operation regimes. The instantaneous and autonomous time response to fault events and its capability to recover after fault clearances, makes this kind of SFCL an attractive device to protect electric power grids [23], [24] and [25].

Due to assembly simplicity, a previous work [6] has considered the primary and secondary of the limiter placed on different core limbs. Nevertheless, there is a likelihood of such assembly to be not fully optimized in terms of performance. The performance can be evaluated by the voltage drop over the primary coil terminals of the limiter as function of the line current and linked flux, which is expressed analytically as

$$u(t) = \mathrm{r} \cdot i(t) + \frac{d\psi(t)}{dt}. \quad (1)$$

Where u , r , and i are, respectively, the voltage drop, resistance and current of the primary, and ψ is its linked flux. It is considered that the resistance of the primary remains nearly constant over time t .

TABLE I
Characteristics of the Primary of the Limiter

Material	Copper
Number of turns	20, 60 or 80
Inner radius	32 mm
Width	45 mm
Cross section of conductor	1.5 mm^2

TABLE II
Characteristics of the Secondary of the Limiter

Material	HTS Bi-2223
Supplier	Innost
Reference	Bi-2223 insulated
Inner radius of rings	41 mm
Tape width	4.2 mm
Tape thickness	0.23 mm
Critical current at 77 K	90 A

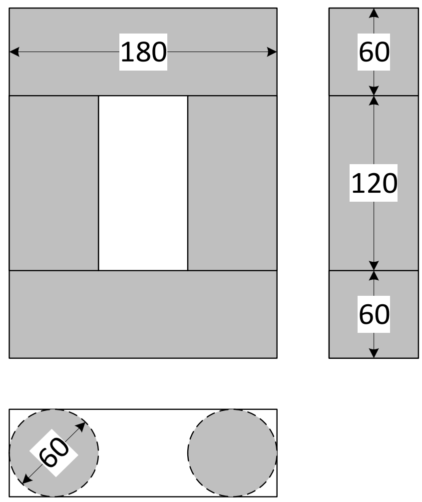

Fig. 1. Dimensions (in millimeters) of the magnetic core used to perform the limiter.

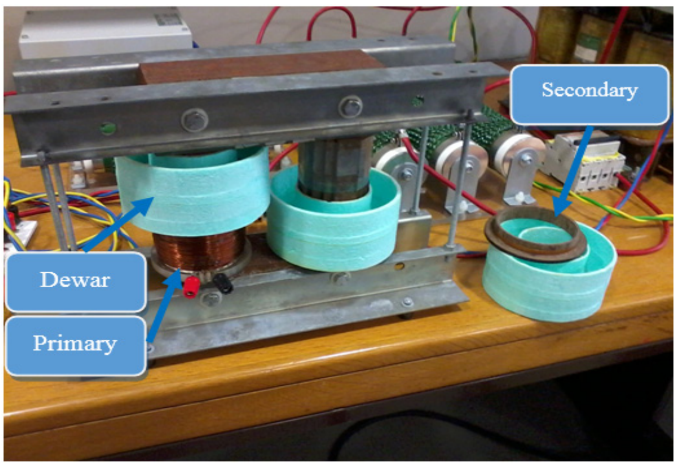

Fig. 2. SFCL prototype with primary and secondary. The primary is wrapped around an acrylic holder, while the secondary is wrapped around a Celeron holder and placed inside a Dewar.

Fig. 3. View of the secondary, built by two first generation superconducting tapes wrapped around a Celeron holder.

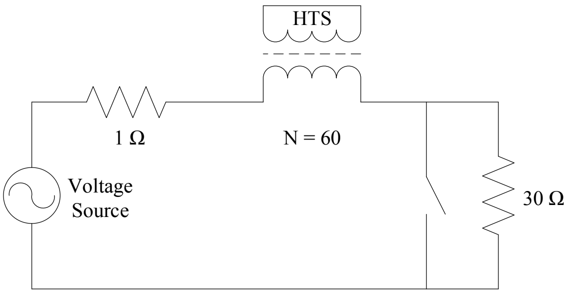

Fig. 4. Diagram of the test circuit. Short-circuit faults are intentionally induced by nulling the load, which is carried out by closing the circuit-breaker.

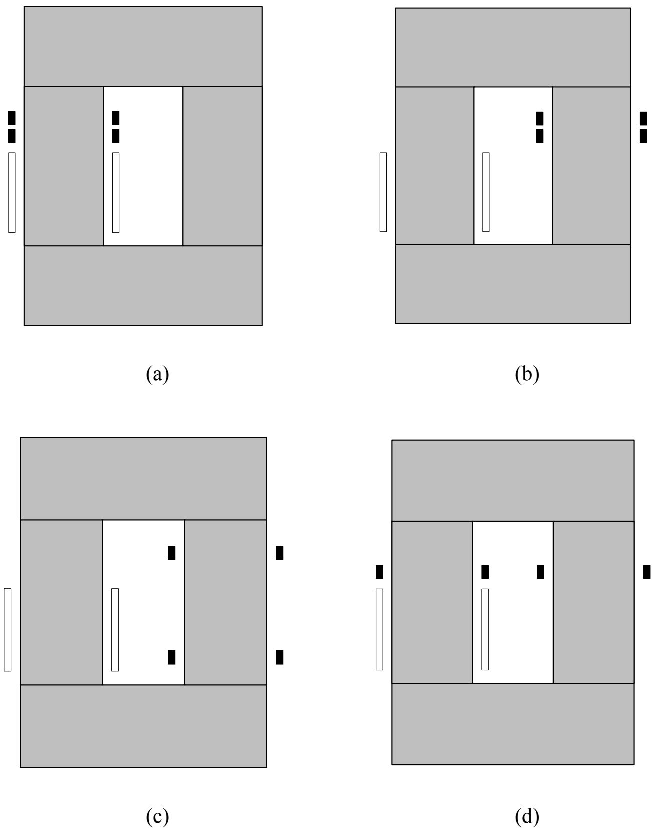

Fig. 5. Different configurations of the SFCL. The primary and secondary coils are painted with white and black background, respectively. Dewars are used to keep superconducting coils below their critical temperature. (a) Configuration A. (b) Configuration B. (c) Configuration C. (d) Configuration D.

The SFCL prototype is built considering a two-legged magnetic core, whose dimensions are depicted in Fig. 1. The developed prototype is shown in Fig. 2, in which the primary with 60 turns and a secondary (placed inside Dewars with liquid nitrogen) with one or two HTS rings of Bi-2223 are chosen, being shown in Fig. 3. The characteristics of the primary and secondary are presented in Tables I and II, respectively.

III. Experimental Results and Discussion

The experimental results were carried out on the developed prototype by means a test circuit as depicted in Fig. 4. The current in the circuit, the voltage drop over the terminals of the primary as well as its linked flux were measured. The measurement of the linked flux with the primary is carried out by integrating the voltage drop over the terminals of an auxiliary coil. In order to evaluate the current limitation, prospective currents are also computed by measuring the voltage provided from the source and the impedance of the circuit. The measurements were made with National Instruments NI-6009 data acquisition board and afterward processed in LabView Signal Express and Microsoft Excel.

The experimental setup is based on an 80 V voltage source feeding a 30 Ω load and a circuit-breaker which is used to intentionally introduce faults in the circuit in order to observe the performance of the limiter. The 1 Ω resistance is used to provide an image of the current in the circuit by measuring its voltage drop.

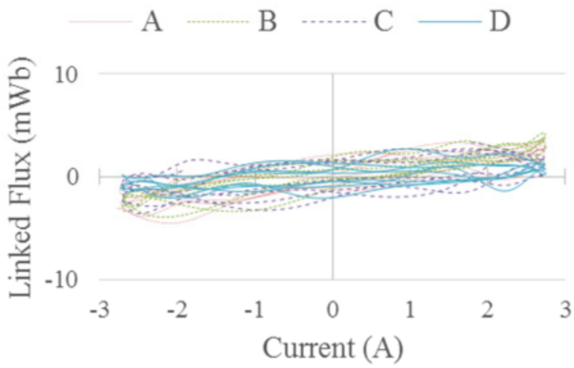

Fig. 6. Characteristic of the linked flux as function of line current during the normal operation regime.

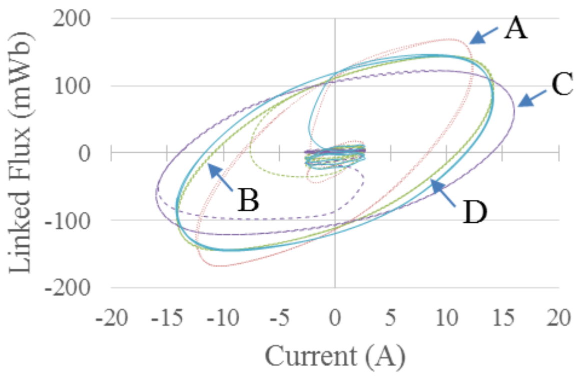

Fig. 7. Characteristic of the linked flux as function of line current during the transition from fault operation regime to normal operation regime.

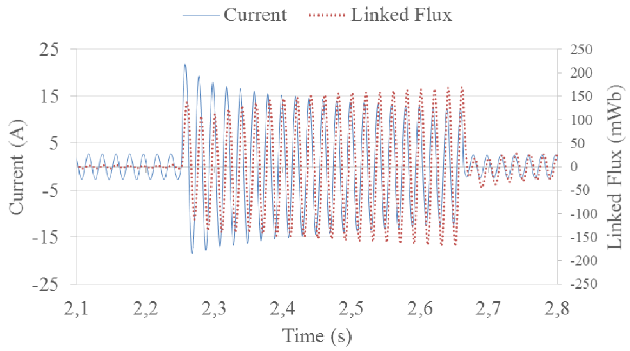

Fig. 8. Fault current limitation performance for prospective currents of 80 A regarding configuration A.

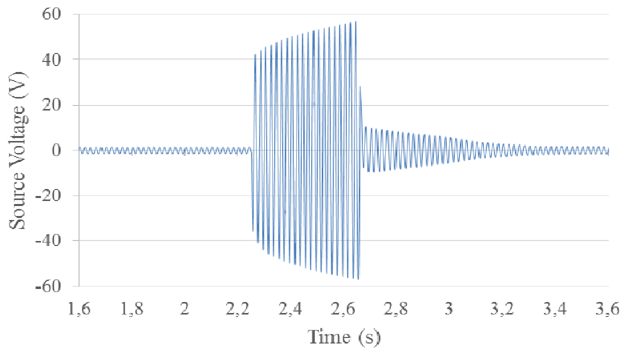

Fig. 9. Voltage drop over the terminals of the limiter for prospective currents of 80 A regarding configuration A.

TABLE III
MAXIMUM MEASURED VALUES AT NORMAL OPERATION REGIME

Configuration	Current (A)	Linked Flux (mWb)
A	2.8	4.6
B	2.7	5.2
C	2.7	3.6
D	2.7	2.9

TABLE IV
MAXIMUM MEASURED VALUES AT FAULT OPERATION REGIME

Configuration	Current (A)	Linked Flux (mWb)
A	12.4	169.1
B	14.2	143.7
C	16.0	122.5
D	14.2	146.4

TABLE V
MAXIMUM MEASURED VALUES FOR TIME RESPONSE OF CONFIGURATION A

Normal Operation	
Current (A)	12.4
Linked Flux (mWb)	4.6
Fault Operation	
Peak Current (A)	21.9
Prospective Current (A)	80.0
Linked Flux (mWb)	169.1

Four different configurations of the SFCL were performed, as it can be seen illustrated in Fig. 5. In each configuration, the primary keeps fixed whereas the secondary and dewars are placed on the magnetic core according to the following design criteria:

- Configuration A: Two HTS rings close from each other placed on the same limb of the primary. One dewar is used.
- Configuration B: Two HTS rings close from each other placed on the opposite limb of the primary. One dewar is used.
- Configuration C: Two HTS rings far from each other placed on the opposite limb of the primary. Two dewars are used.
- Configuration D: One HTS ring on each limb. Two dewars are used.

A. Normal Operation Regime

At normal operation regime is intended negligible voltage drop over the terminals of the limiter, which means that (1) should be as minimum as possible. Since the voltage drop due to ohmic resistance of the primary remains nearly constant in each experiment, it is important to analyse the part that is due to linked flux variances. This part is related to the magnetic shielding performed by the secondary.

The characteristic of the linked flux as a function of line current is illustrated in Fig. 6. The characteristics of all configurations show low flux variance without major differences, which means that each configuration performs effective magnetic shielding, minimizing the penetration of magnetic flux in the core and thus low voltage drop at the terminals of the limiter.

The maximum measured values regarding each configuration are presented in Table III. The maximum values of the current are nearly identical on each configuration and there are no major differences in the maximum values of linked flux.

B. Fault Operation Regime

At fault operation regime, high current limitation capability is desired, meaning that the SFCL must add high impedance to the circuit, through the loss of magnetic shielding, in order to limit the current. This feature is achieved since there is magnetic flux variance in the magnetic core of the limiter prototype due to the transition of the superconducting tape to the resistive state. This transition is dependent of the magnetomotive force in the primary [3] and [26].

The excursion of the linked flux with the primary as function of line current from a transition between the fault operation and normal operation is depicted in Fig. 7 and it is possible to observe that the configuration A presents the better performance since lower current and high linked flux magnitudes are achieved. Configurations B and D have a very similar excursion and, the configuration C, is the one that present worst performance.

The maximum measured values regarding each configuration are presented in Table IV. As it is observed by the hysteresis loops, the best performance is achieved by the configuration A, where the current was limited to 12.4 A, and consequently the linked flux is the highest of all configurations, 169.1 mWb. The configurations B and D show quite similar results between each other and the configuration C presents worst results, allowing to conclude that splitting the secondary does not constitute any advantage, even leading to a more complex design of the device.

C. Time Response of the Limiter

The time response performance of the limiter (on its configuration A) under a transition between the normal operation and fault occurrence and vice-versa is shown in Fig. 8, where the limited current and linked flux are depicted. A prospective current of 80 A is limited to 21.9 A in the first peak and previously to 13.1 A. The amplitude of the linked flux, at fault operation regime is growing continuously with time, enabling growing current limitation. After the fault suppression, the limiter re-establishes its normal operation principle in less than one second, as it can be seen in Fig. 9.

Table V presents the maximum measured values. Considering the prospective current and the limited peak current it is found that the prototype, on its best configuration (configuration A), allows to achieve at least 72.6% of current limitation.

The reduced recovery time after a fault clearance constitutes a great advantage when compared to resistive type limiters [27] and [28].

IV. Conclusions and Further Work

The growing demand for power provided from distributed generation, mostly from renewable energy sources, requires optimized, controlled and secure connections to distribution electric grids in order to deal with the variable energy production paradigm. SFCLs help to reduce short-circuit current levels in power grids, which allow to avoid their upgrading.

In this paper, the design and test of a magnetic shielding superconducting fault current limiter was described. This study concludes that, at a normal operation regime, all the configurations assure effective magnetic shielding, however the configuration which has the secondary placed on the same limb as the primary (configuration A) provides better current limitation during fault operation. From the experimental tests, this configuration showed prospective currents of 80 A limited to 21.9 A in the first peak and previously to 13.1 A. Splitting the secondary does not constitute any advantage, it even leads to a more complex design and worst performance in terms of current limitation is achieved.

The design of a prototype in which primary and secondary are placed concentrically constitutes a design challenge but needs to be conducted in the future to evaluate and compare with the configurations considered in this work. Also as the further work, the measuring of the induced currents in the HTS tapes is important in order to detect hot-spot formation during quench of the HTS tapes.

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