Resistive Type Superconducting Fault Current Limiters: Concepts, Materials, and Numerical Modelling

H. S. Ruiz, X. Zhang, and T. A. Coombs

Abstract—**In recent years, major industrialized countries have began to be concerned about the need for developing strategies on the integration and protection of the growing power capacity of renewable source energies, attracting back their interest on the development and understanding of superconducting fault current limiters (SFCL). The reasons for this are simple: a SFCL may offer a rapid, reliable and effective current limitation, with zero impedance during normal operation, and an automatic recovery after the fault. Nowadays, most of the R&D projects have turned towards to the study of the resistive type SFCL due to their potential to be small, and the likely decrease in price of 2G coated conductors. Thus, in this paper we provide an updated review on the state of the art of resistive type SFCL, emphasizing on the different approaches for the numerical modelling of their local physical properties, as well as on the already tested experimental concepts. Comparison between the properties and characteristics of different resistive-type SFCL using different superconducting materials is presented.**

Index Terms—**Fault current limiter, power system faults, coated conductors, superconducting materials.**

I. Introduction

One of the major challenges the US and EU Member States will face in the coming decades is to make its energy system clean, secure, and efficient, while ensuring its industrial leadership in low-carbon energy technologies contributing to the development of a sustainable economy as the uncertainty over future global economic growth elevate crude oil price risk going forward [1]. To help achieve such ambitious objectives the energy system needs to evolve to accommodate, among others, much higher levels of integration of renewable energy, as well as to protect and or replace the currently installed electric power grid in a prospective market of about 50 billion dollars per year within 2030 [2]. As higher is the number of electric power systems connected to a grid higher is the need to consider topological measures leading to a permanent increase of the impedance not only at fault operation but also at nominal operation. It basically decrease the power system stability, because the preventive measures such as installing serial reactor and replacing circuit breakers or fuse devices changed the operating and transient characteristics of the electric power system. However, with the capability of the superconductors of rapidly increasing its impedance, a superconducting fault current limiter can overcome these weaknesses operating with little to no impedance until a fault current event occurs. Moreover, thanks to their fast transition from a low to a high impedance, as well as to its automating resetting from the fault condition to its nominal operation when the superconducting state is recovered, a superconducting device can limit, in a very short time, the value of any fault current. A schematic illustration summarizing some of the most important features on the operation of a resistive type SFCL is shown in Fig. 1.

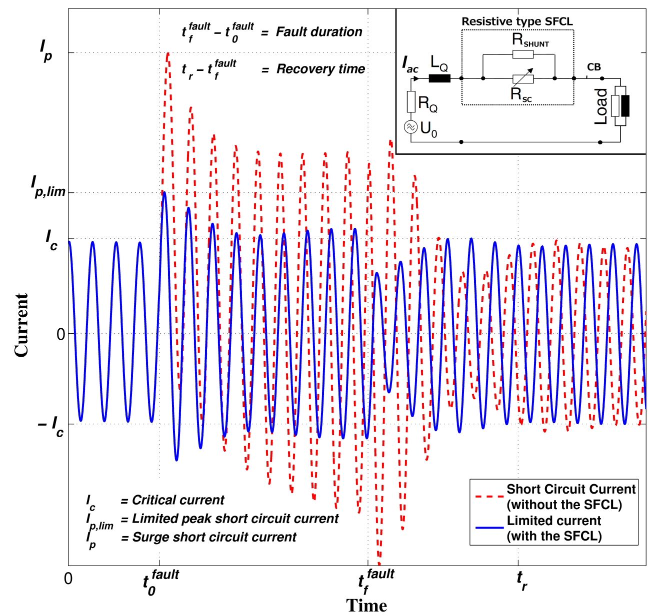

Fig. 1. Illustration of the current profile for a fault circuit with a connected resistive-type SFCL.

Despite multiple concepts for the designing of SFCLs have been conceived in the last two decades [3], resistive-type SFCLs are the most promising due to their potential to be smaller, and the expected decreasing of prices for 2G coated conductors. Thus, in this paper we aim to provide a state of the art study covering the current physical understanding and latest projects on the practical implementation of resistive-type SFCLs, called in what follows just SFCLs for the sake of simplicity. For other concepts of superconducting fault current limiters we suggest to the reader [3], and references therein.

The paper is organized as follows. In Sec. II we review the

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major progresses with regard to the practical implementation of resistive-type SFCL in terms of the concepts developed and the superconducting material used. Then, in Sec. III several numerical models for the study of the electromagnetic and thermal properties of resistive-type SFCL are outlined in terms of the available mathematical formulations, computational packages, and studied materials. Finally, a brief summary of the main issues discussed on this paper is given.

II. Practical implementation of SFCL: Field Test Status and Other Considerations

From the basic operational concept of a SFCL, the characteristics and requirements of the superconducting (SC) materials are essentially the same [3]. However, in terms of its practical implementation an accurate sizing of the amount of material needed is a serious challenge which depends on the physical properties of the entire system. For instance, in the case of low J_c materials, and assuming that the superconductor heats up uniformly during a broad transition beyond the critical state [4], the amount of material needed can be roughly estimated by the need to drop the supply voltage on the SFCL once the transition to the normal state is reached by the condition $J > J_c$. On the other hand, for high J_c materials the amount of material is mainly determined by the need to absorb the thermal energy in a fault without irreversible degradation, but the material volume must still be low enough for heating up above T_c before reaching the rated time for the aperture of a protective circuit breaker.

In the case of SFCL using low temperature superconducting materials (LTS) such as NbTi alloys [5]-[6], very successful projects have been carried on before the manufacturing of high temperature superconducting materials (HTS) with reproducible quality. Nonetheless, despite the cost of NbTi alloys into the superconductivity market is very competitive, in general, LTS SFCL seems not be possible to be commercialized due to the high cooling cost and the difficulties to manage a cryogenic system with a nearly zero helium loss. However, a HTS SFCL is intentionally designed to operate at liquid nitrogen temperature, substantially reducing the cryogenic cost of the entire system.

HTS materials in diverse configurations have been extensively used for the prototyping of SFCL worldwide (Table I). In 2003, the first field test of a SFCL for medium-voltage-level applications named CURL10 was built with melt cast processed Bi2212 tubes cut into bifilar coils, showing virtually no degradation of the material after two years test [7]. Using the same bulk material, but cut into monofilar coils, the first commercial medium voltage SFCLs were released in 2009 by Nexans SuperConductors GmbH for two customers [8]: Applied Superconductor Limited in UK, and Vattenfall in Germany. Most recently, a SFCL with a rated power of 4.4 MVA (11 kV,0.4 kA) was installed in the UK earlier 2012, and it has been operating since middle 2013 [9]. Also, a novel concept of magnetic field assisted quench propagation was developed in order to overcome the difficulties on the scaling of the bifilar concept to high voltages, with a successful proof-of-concept test achieved in the United States in 2005 [10]. At demonstration scale, other bulk geometries made of Bi2212 were tested in Switzerland reporting a medium voltage SFCL with a rated power of 6.4 MVA (8 kV, 0.8 kA) [11]. On the other hand, Bi2223/Ag multifilamentary tapes have also shown to be feasible for the prototyping of SFCLs, but a commercial implementation of these devices has not been pursued. Two major research projects were conducted on the base of this material, and small scale prototypes were successfully tested: The first project was conducted in Brazil aiming for the design of a SFCL with a rated power of 6 MVA (15 kV, 0.4 kA), but only laboratory scale proofs for the validation of the Bi-2223/Ag concept were reported [12]. Then, into this framework, the other project of relevance was conducted in Italy for a SFCL with a rated power of 40 kVA (500 V, 80 A) [13]. More exotic HTS materials have also been studied in the past for the prototyping of SFCL at small scale with very promising results [14]. However, nowadays the most prominent alternatives have relied on the use of YBCO coated conductors, also called the second generation (2G) of HTS, due to their larger cooling surface area (in contrast with the bulk volume ratio), better performance under the electro-mechanical stress and thermal shocks induced by fault currents, as well as an increased design flexibility for practical purposes.

Before the commercial appearance of the 2G HTS conductors, many efforts were done and are to continue in order to determine the correct combination, sizing, deposition technique, and physical properties of the different materials composing this kind of structure (HTS, substrate, buffer, etc...). In this sense, the research on SFCL also played a major role and deserve to be reminded. One of the first successes on the concept proof for using YBCO thin films in SFCL was achieved by Siemens-Germany during the 90s, where different deposition techniques and substrates were compared and tested for low, medium, and high voltage rated powers [15]. Iin the same period other no less important designs were also proposed by companies like Toshiba in Japan [16]. Then, in the next decade most of the research on SFCL based upon YBCO thin films was mainly dominated by Japan [17]-[20] and Korea [21] by pursuing some novel designs.

The first successful proof-of-concept test of a SFCL based upon coated conductors was reported in 2003 in the framework of the European SUPERPOLI project [22]. In this project, YBCO coated stainless-steel tapes were fabricated for the designing of three modules connected in series with minimum current limitation effect at 2.4 kA, successfully operating (with no material degradation) at 20 kV for prospective short-circuit currents up to 50 kA. Other YBCO coated conductors with specific features were also tested for the same purposes in Germany [23], and with the gained experience different designing concepts were further proposed for the use of commercial 2G HTS tapes [24]. Under this framework, Superpower Inc. was the first that shown the feasibility of using commercial tapes for the manufacturing of SFCL at low and high power grids [25]. Almost at the same time, in Korea, two different size coils made of American Superconductor (AMSC) tapes were successfully tested for a SFCL rated on (13.2 kV, 630 A), leading to the conceptual design of the

TABLE I
CURRENT STATUS OF TESTED RESISTIVE SFCLS

Material	Data	Year/Ref[†]	Country / Lead Co.
NbTi	6.6 kV, 1.5 kA	1993 / [5]	JPN / Toshiba
NbTi/CuNi	40 kV, 315 A	1996 / [6]	FRA / Alsthom
Bi2212	6.9 kV, 600 A	2003 / [7]	DEU / ACCEL-Nexans
Bi2212	8.6 kV, 800 A	2005 / [10]	USA / DOE-EPRI
Bi2212	12 kV, 100 A	2009 / [8]	GBR-DEU / Nexans
Bi2212	12 kV, 800 A	2009 / [8]	GBR-DEU / Nexans
Bi2212	11 kV, 400 A	2012 / [9]	GBR / Applied Superc.
Bi2223	500 V, 80 A	2005 / [13]	ITA / CESI
YBCO[‡]	765 V, 135 A	1999 / [15]	DEU / Siemens
YBCO[‡]	200 V, 1kA	2004 / [17]	JPN / Mitsubishi
YBCO[‡]	6.6 kV, 200 A	2005 / [21]	KOR/ KEPRI
2G HTS	20 kV, 2 kA	2003 / [22]	EU / Superpoli project
2G HTS	6.6 kV, 600 A	2009 / [27]	JPN / Toshiba
2G HTS	115 kV, 1.2 kA	2009 / [28]	USA / AMSC
2G HTS	22.9 kV, 630 A	2012 / [26]	KOR / KEPRI[§]
2G HTS	10 kV, 200 A	2012 / [30]	CHN / Shangai J. U.
2G HTS	12 kV, 533 A	2012 / [31]	DEU / Ensystrob proj.
2G HTS	24 kV, 1kA	2013 / [32]	EU / Eccoflow project

[†] For each material, in chronological order for the year when the test report was disclosed. Data are presented according to the phase to ground voltage and rated continuous current.
[‡] YBCO Thin films
[§] Resistype type concept for the SC module and the current limiting module has been used. The SC module was not used for current-reduction purpose, but for fault current sensing and current conmmutation with a parallel fast-switching module. In this sense, the KEPRI limiter stands as a hybrid concept.

SFCL rated on (22.9 kV, 630 A) currently operating at the south-east of Seoul since 2011 [26]. In Japan, a consortium formed by different companies and research institutes, has successfully tested a (6.6 kV, 600 A) SFCL, optimizing the thickness of the silver protecting layer of the AMSC tape, and laminating it with a high-resistive stabilizing metal layer [27]. In the same year, AMSC, Nexans, Siemens, and Los Alamos National Laboratory, have reported the successful test of a (138 kV, 1.2 kA) SFCL installed in the Southern California Edison Grid as part of the DOE project called Superlimiter [28]. Continuation of this project was granted by the DOE (DE-FC26-07NT43243) in 2009 [29], but the final project report has not been yet released. In China, Shanghai Jiaotong University has manufactured their own 2G HTS tapes for the testing of a (10 kV, 200 A) DC SFCL-concept in 2012 [30]. On the other hand, within the German government funded project called ENSYSTROB, the worldwide largest operating SFCL on the base of 2G HTS conductors so far, has been installed in the Boxberg grid, successfully operating with a medium voltage rated power of 6.4 MVA (12 kV, 533 A) [31]. Then, in the framework of the recently ended European project ECCOFLOW [32], a (24 kV, 1 kA) SFCL has been designed to meet the specific requirements of two hosting utilities, Endesa in Spain, and VSE in Slovakia, but the testing results have not been yet disclosed.

Finally, is worth mentioning that in spite of the number of projects on SFCL based on MgB2 wires is smaller [33]-[35], their low manufacturing cost featuring high n-values, further the possibility of using liquid hydrogen as conductive-coolant [36], makes MgB2 wires highly attractive for the prospective commercial deployment of this technology.

III. NUMERICAL MODELS AND SIMULATION METHODS FOR RESISTIVE-TYPE SFCLS

As it has been stated, the R&D progress with the use of SC materials has already shown its technical feasibility for the commercial deployment of SFCLs. However, for the further commercialisation of these devices, is still of utter concern the lack of knowledge that we have about how to control the physical properties of the SC structures in real scenarios operating at different voltage rates and fault levels. In fact, for a SC material the process of going normal is not easy to model as it takes the superconductor through transient states with high electric fields where it is impossible to measure their local physical properties. Nevertheless, some theoretical assumptions can be made in order to understand and predict some relevant features for the operating of a SFCL.

As there is not still consensus on the minimum level of complexity of the grid from the numerical point of view for even specific distribution operators, below we summarize only the theoretical models capable to consider the local physical properties (thermal and electrical) of the materials involved for the designing of a SFCL. Thus, one of the first models that attempted to describe the electro-thermal properties of a SFCL was introduced by our group in 2002 [37], in order to study the effects of inhomogeneities and the occurrence of weak links (cracks) in superconducting bulks, by assuming a 2D electrical circuit model for thermally coupled SC grains with independent $E-J$ properties. This model is currently being extended to a fully 3D electro-thermal model for considering more realistic scenarios with different SC structures (bulks, thin films, and 2G HTS tapes).

Beyond the 1D approaches (slabs or infinitely thinner strips) for sizing the superconducting materials, the specific density of electromagnetic losses in a SC, which is equalized to the thermal dissipation energy for studying SFCLs, can be calculated by exact analytical methods only in the case of a cylindrical wire of infinite length (2D), which in terms of the direction of the current density is a 1D problem [38]. Thus, below we have scrutinized the different numerical models available in the literature in terms of the dimensionality of the sample, the number of spatial freedom degrees on the involved physical variables, and consequently on the mathematical formulation used for dealing with the electromagnetic problem. Starting with the 1D analysis, despite than these models cannot give account of the electromagnetic or thermal response inside of the elements conforming a SFCL, neither study their detailed structure, the SFCL can be simulated into an equivalent electrical circuit dealing with all kinds of short-circuit failures, as a single non linear resistor obeying the $E-J$ power law, $\mathbf{E} = E_0 \cdot (\mathbf{J}/Jc)^n$, for describing the superconducting state. Into this framework, most of the models have been developed in terms of the time-domain transient analysis method, customarily embedded by simulation packages such as: ATP/EMTP [39], PSCAD/EMTDC [40], and MATLAB/Simulink [41]. Proprietary packages with on-purpose advanced features for thermal transient analysis have been also developed under this scheme [42]-[43]. On the other hand, for dealing with 2D and 3D symmetries, the numerical modelling of SFCL based on finite element methods (FEM) has been more extensively developed due to the availability of commercial computational packages, capable to use different mathematical formulations for solving the Maxwell equations, i.e., allowing the calculation of the specific density of power losses $\mathbf{E}\cdot\mathbf{J}$ (per element), whilst, in general, the Fourier heat transfer problem can be solved by the Newton-Raphson method. However, it is worth to mention that for a proper calculation of the losses in the case of a SFCL, an additional assumption has to be made in order to consider the rate of heat transfer at the cooling surfaces. For instance, if the SFCL operates into a LN2 cryogenic bath, then the numerical model depends on the *shape* of the boiling-off curve for the LN2 in the whole range of temperatures of interest, i.e., for temperatures greater than 77 K and lower than the melting temperature of the superconducting material. Unfortunately, there is still not consensus about the proper function for the boiling-off curve for all the cases, because it depends on the pressure conditions, quality, area, and orientation of the surface of the body in contact with the LN2 [44]. Thus, below we suggest to the reader to consider the validity of the numerical models just in terms of the solution for the electromagnetic problem.

According to our knowledge, the first 2D FEM model for the study of SFCL, with SC thin films obeying the $E-J$ power law [45], was developed into the framework of the so called $T-\Phi$ formulation which uses the current vector potential $\mathbf{T}$, and the scalar potential Φ, as state variables with $\nabla\times(\mathbf{T}-\mathbf{T}_0)=\mathbf{J}$ and $\mathbf{H}=\mathbf{T}-\mathbf{T}_0-\nabla\Phi$, where $\mathbf{T}_0$ is an auxiliary potential for imposing the transport current condition. The same strategy was later adapted for the thermal modelling of 3D isotropic Bi2212 bulks in the CAST package [46] and then, for YBCO/Au thin films in the FLUX package [47], both with constrained profiles of current flowing in two directions only. In this sense, the $A-$formulation which implies the analytical solution of the self and mutual inductance matrices for profiles of currents J with defined symmetry, i.e., with a straightforward calculation of the magnetic vector potential $\mathbf{A}$ [48], can be used for 2D electromagnetic problems regarding the components of the state variables, whilst the thermal analysis can be implemented for 3D symmetries. In the case of Bi2212 (wires and bulks) and YBCO thin films, this approach has been implemented for the numerical modelling of SFCL by using the FLUX2D package, plus additional subroutines for the thermal analysis [49]. It can be also implemented by developing proprietary codes which allow consider not only the $E-J$ power law for the superconducting material [50] but also the more fundamental law of the critical state $J\leq J_c$ [51].

Finally with the emergence of more robust computational packages including multiple physics environments, like COMSOL, a broader number of numerical models have been developed in the recent years. In these cases, the partial differential equations system defined by the classical Maxwell equations are solved by imposing boundary conditions for the expected pattern of magnetic field $\mathbf{H}$ at some regions of the space ($H-$formulation). This method although very powerful does not allow to ensure that the transient solution for large scale nonlinear systems has not been anchored to local minima solutions instead of finding a global and unique solution. It creates major difficulties to assure that all the physical phenomena inside of the superconducting material are being properly described when the boundary conditions for $\mathbf{H}$ are usually imposed far away of the material itself. However, for 2D systems with J constrained to flow in only one direction reliable solutions for the electromagnetic problem can be achieved, whilst the heat transfer problem is solved via the transient conduction equation. This strategy has been used for describing the electro-thermal properties of single coated conductors [52] -[53], stacks of 2G HTS tapes [54], and 2G HTS coils [55], as active elements of the SFCL. For the sake of simplicity, COMSOL also allows the 1D modelling of SFCL, with differences between the theory and experimental measurements of about 20-40% in 2G HTS tapes, decreasing for the case of MgB2/metal conductors [56].

IV. Observations and Conclusions

It has been established that the integration of renewable electricity into the grid market must pursue the decreasing on the operation and maintenance costs of the current electricity networks, where the need for a promptly technology deployment of the resistive-type superconducting fault current limiters (SFCL) is imperative. Thus, in this paper we have presented an updated review of the several successful field tests demonstrating the technical feasibility of the resistive type SFCL. Likewise, from the theoretical point of view, due to the remarkable challenges that imply the further optimization of these devices, we have presented a comprehensive review of the different existing numerical models based upon different theoretical formulations, concepts, computational packages, and superconducting materials.

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