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Modelling and Parameterization of Resistive Superconducting Fault Current Limiters

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Abstract. The present paper introduces the theoretical modelling of resistive-type Superconducting Fault Current Limiters (SFCL), which are the most common type in latest AC installations. SFCLs provide one of the most promising solutions for limiting fault currents in power grids by using superconducting materials. The study considers two approaches: the simplified exponential model and the thermo-electric model, based on The parameterization of both model types is introduced hereby, and in order to verify the influence of design parameters, both model types are implemented and simulated with MATLAB Simulink. The paper presents modelling issues and simulation results.

Key words

High temperature Superconductor (HTS), Superconducting Fault Current Limiter (SFCL), resistive SFCL.

1. Introduction

Fault Current Limiters (FCLs) are used to limit, with high speed, very high currents during faults. Nowadays, with higher penetration rates of renewable energies and demand level increase, short-circuit current are rising. Thus, FCLs can provide a promising alternative to cope with those currents by mitigating them. For this purpose, limiters can be installed at bus-ties, transformer positions, or distribution feeders.

Among other technologies, Superconducting Fault Current Limiters (SFCLs) provide one of the most promising solutions for limiting fault currents in power grids by using superconducting materials. The use of SFCLs is currently being studied not only for AC systems, but also for HVDC (High Voltage Direct Current) systems, where they can reduce fault currents to acceptable levels allowing DC circuit breakers with reduced rating to operate quickly and reliably [1].

Under normal operation, SFCLs present no resistance, if temperature is maintained within the critical temperature. But for faults exceeding a limit current, the resistance increases and thus, fault current is limited. Hence, compared to other alternatives, they have negligible impedance at normal conditions, fast and effective current limitation within the first current rise and repetitive operation with fast and automatic recovery [2].

This paper aims to study the challenges related to modelling and parameterization of resistive SFCLs. Thus, in Section 2 the latest projects of SFCLs are reviewed, in order to identify current trends regarding most common limiter types, superconductor materials, installation point and function. Then, Section 3 introduces different resistive SFCL modelling approaches, along with device parameterization practices as proposed in the literature. Finally, the performance of simplified SFCL models is compared to a more complex thermal-electric model in Section 4, based on a Medium Voltage (MV) radial grid.

2. Practical implementation of SFCLs

There have been proposed four main types of SFCLs: resistance-type, rectifier-type, saturated-core-type and magnetic-shield-type. Resistive SFCLs show several advantages, such as a simpler structure, smaller size and lower cost [3]. Therefore, nowadays resistive SFCLs are the preferred option for both AC and DC systems.

Table I gathers some of the latest projects involving the installation of SFCLs in AC grids, starting from 2010. Most of the applications correspond to resistive SFCLs based on second-generation coated conductor such as YBCO tapes in MV. The superconducting material YBCO has a slower change in resistivity with respect of temperature, but a faster recovery after quenching [4]. In [5], it was concluded that YBCO tapes have better characteristics for use in a superconducting fault current limiter operating at 77 K. SFCL prototypes based on multistrand MgB_2 have also been reported in [6], with a significant potential due to their low-cost and simple manufacturing process [7]. However, superconductivity is achieved at a lower temperature and quenching resistance

Table I. - Latest SFCL projects

MANUFACTURER	DATA	TYPE	SUPERCONDUCTOR	FIELD TEST	FUNCTION	REF.
Innopower (China)	220 kV, 300 MVA	Saturated core	BSCCO tape	Yes (2010)	--	**[8]**
Kepco (Korea)	22.9 kV, 3 kA	Hybrid	YBCO tape	No (2010)	Transformer protection	**[9]**
Nexans (Germany)	12 kV, 800 A	Resistive	BSCCO bulk	Yes (2011)	Feeder protection	**[10]**
RSE (Italy)	9 kV, 3.4 MVA	Resistive	BSCCO tape	Yes (2012)	Feeder protection	**[11]**
AMSC, Nexans, Siemens (USA)	115 kV, 1.2 kA	Resistive	YBCO tape	No (2012)	--	**[12]**
Zenergy (USA)	138 kV, 1.3 kA	Saturated core	BSCCO tape	Yes (2012)	Transformer protection	**[13]**
Nexans (Spain)	24 kV, 1005 A	Resistive	YBCO tape	Yes (2013)	Bus-bar coupling	**[14]**
Nexans (UK)	12 kV, 1600/1050 A	Resistive	YBCO tape	Yes (2015)	Bus-bar coupling	**[15]**
RSE (Italy)	9 kV, 15.6 MVA	Resistive	YBCO tape	Yes (2016)	Transformer protection	**[16]**

is smaller. Most active countries in the development of SFCLs are Korea, China, Germany, the UK, and the USA.

On the other hand, SFCLs are also being studied as part of the protection system of HVDC networks, combined with fast acting DC breakers. Resistive SFCLs are the preferred option. However, no prototype or real installation has been reported so far, although practical SFCL systems could be a reality by the 2020s [1].

Therefore, the modelling and parameterization of superconducting limiters is important in order to analyze and design existing or planned installations in both AC and DC systems.

3. Modelling of resistive SFCLs

A. Operation principles of resistive SFCLs

Within critical conditions, resistive SFCLs show no resistance for current. During this period, they are operating under a *superconducting* state. Under faults, current increases highly and so does the resistance of superconductors due to the rise of the superconductor temperature. This stage is commonly called the *flux-flow* state. Once the superconducting material is fully quenched, the SFCL operates in *normal conducting state*. After the fault is cleared, resistive SFCLs need a recovery time, during which the element is cooled until it returns to its *superconducting* state.

B. State-of-the-art of resistive SFCL modelling

Concurrently with the commercialization of the first SFCLs, different types of simulation models have been presented, from simple to more complex models. The resistive SFCL models include the complete limiter, which consists of the superconducting material (Rsc in Fig. 1) and a parallel resistor (Rp in Fig. 1), which reduces overvoltages during fault and diverts the fault current to avoid overheating the superconducting material **[17]**.

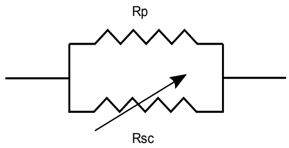

Fig. 1. Resistive SFCL model

The resistance Rp may be attached to the superconductor (e.g. coating in **[18]**) or external. Thus, it results from the resistivity of the metal that binds to the superconductor during the manufacturing process to reduce hot spots **[19]** or the resistance (or inductance) installed outside the cryogenic environment in parallel to reduce the energy dissipated in the superconductor **[20]**. Sometimes the parallel resistance is the combination of the bound resistance and the external resistance. In **[4]** two resistances are included in parallel with the superconductor: the substrate and the silver coverage. On the other hand, although the superconducting coils are wound so that the inductance is cancelled, the elimination is not total and this may be important for AC applications **[21]**.

Limiters are often made up of several units in series, to achieve the required ratings. In Sung et al. **[22]** each unit of superconductor consists of the resistance of the stabilizer Rns, the resistance of the superconductor Rnc, and the inductance of the coil Ln. In **[23]** a very similar model is presented. However, the studies often neglect both the parallel resistance **[24]** and the inductance **[22]** to simplify the analysis.

In resistive SFCLs, the resistance of the superconducting material varies with current density, and hence, with temperature. Depending on the application, this resistance can be represented by a simple time-dependent equation (a step, linear or exponential function) or by thermo-electric models, which can also vary in complexity. This paper is focused on a exponential model **[25]** and a common thermo-electric model in literature, based on **[17]**.

C. Simplified exponential model

Exponential models agree with higher precision with real experimental results than other simplified models such as the step or the linear model. In this model, the resistance of the superconductor (Rsc) under a critical current (Ic) is negligible. For higher currents (fault situation), resistance increases exponentially with time (t) until a maximum value (Rmax) when the limiter is fully quenched according to equation (1). τ corresponds to the time constant and t_0 to the start of the quenching process.

$$R_{sc}(t) = R_{max} \cdot \left(1 - e^{-((t-t_0)/\tau)}\right) \quad (1)$$

D. Thermo-electric model

In this model, the resistance of the superconductor is represented by equation (2), where E(t) is the electric field, lsfcl is the superconductor length and i(t) the instantaneous current flowing through the superconductor. The electric field must be calculated at each instant according to an E-J characteristic during the superconducting, flux-flow and normal conducting states.

$$R_{sfcl}(t) = \frac{E(t) \cdot l_{sfcl}}{i(t)} \quad (2)$$

As current increases during a fault, the current limiter will go through those three states. Each state is characterised by a power law (Equations (3) to (5)).

$$E_1 = E_c \cdot \left(\frac{J}{J_c(T)}\right)^{\alpha(T)} \quad (3)$$

$$E_2 = E_0 \cdot \left(\frac{E_c}{E_0}\right)^{\beta/\alpha(77K)} \cdot \left(\frac{J_c(77K)}{J_c(T)}\right) \cdot \left(\frac{J}{J_c(77K)}\right)^{\beta} \quad (4)$$

$$E_3 = \rho(T_c) \cdot \frac{T}{T_c} \cdot J \quad (5)$$

where J_c is the critical current, which must be fitted to experimental data; α and β depend on material processing conditions, ρ is the normal resistivity and T_c is the critical temperature. Jc(T) and ρ(T) can be approximated as linear functions of temperature by equations (6) and (7).

$$J_c(T) \approx J_c(77K) \cdot \left(\frac{T_c - T}{T_c - 77K}\right) \quad (6)$$

$$\rho(T) \approx \rho_c(T_c) \cdot \left(\frac{T}{T_c}\right) \quad (7)$$

During the flux-flow and normal state, power is dissipated and temperature rise versus time can be calculated by (8) [26], where c is the heat capacity per volume.

$$\frac{dT}{dt} = E \cdot \frac{J}{c} \quad (8)$$

Most detailed thermal models also include the cooling process, whereas several authors consider adiabatic conditions.

E. Parameterization of resistive SFCL models

The parameterization of limiter models can be used for studying existing installations, where experimental data of the superconductor behaviour can be available, as well as for analysing the design and implementation of a new SFCL. Based on experimental data, the exponential model in (1) can be fitted, or a matching mathematical model can be deduced. This paper focuses on the design of a superconducting device for specific current limiting conditions.

Thus, in the exponential model, the maximum resistance value R_{max} can be adjusted for a certain current limitation, as indicated by equation (9) for a passive radial grid with an inductive source, as shown in Fig. 2. V represents the voltage at the fault point (phase-to-neutral), I_{sc} the limited short-circuit value and X_s the source inductance. The necessary current limitation can be constrained by the breaking capacity of the circuit breaker downstream. Bus 1 represents the infinite busbar and Bus 2 the Point of Common Coupling (PCC).

$$R_{max} = \sqrt{\left(\frac{V}{I_{sc}}\right)^2 - X_s^{\,2}} \quad (9)$$

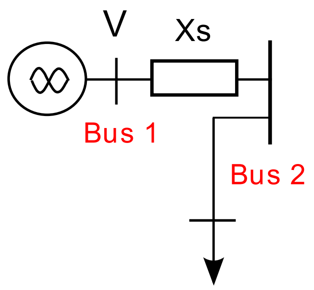

Fig. 2. Passive radial grid

Regarding the time constant, it must be sufficiently low so as to limit fault current during the first peak current. For fast HTS, it is usually 1-3 ms. The fast action of the resistive limiter represents an advantage for DC grids, where short-circuit current increases rapidly. If experimental data is available, both I_{sc} and τ can be fitted. However, R_{max} can be also determined based on transient stability criteria, protection coordination and for optimizing the recovery of superconducting material. The selection of the critical current is also an important parameter in the model. It should be higher than $5I_N$, in order to avoid quenching under overloading situations.

Parameterization is certainly more complex in thermo-electric models. On the one hand, geometry of the limiter, thermo-electric properties of the superconducting material, as well as thermal characteristics of the coolant (if recovery process is modelled) must be taken into account.

4. Application of SFCL in a MV grid

This section presents the application of a resistive SFCL in a 30 kV medium voltage grid with radial topology, as shown in Fig. 2. The network feeds a three-phase load of

20.78 MVA with a power factor of 0.9 inductive. Initially, the short-circuit capacity at the PCC was 1039.23 MVA, and therefore, the circuit breaker in the feeder was accordingly dimensioned. However, due to an expected increasing penetration of PV energy in the region, the short-circuit level at the PCC can rise up to 1558.84 MVA. Therefore, the existing protection system will be no longer valid. As an alternative, the installation of resistive SFCLs upstream of the circuit breaker for each phase is planned. The model parameterization and simulation results are indicated in the following sections.

The system has been modelled with MATLAB Simulink. Both the exponential and the thermo-electric model approaches include 3 single-phase limiters, which have been theoretically described in Section 3.

A. Simplified exponential model

The maximum resistance of the SFCL in steady-state has been calculated with (9). According to the specifications, the short-circuit current must be limited to 20 kA, and as a result, Rmax will be set to 0.646 Ohm. The rest of the parameters of the exponential model will be adjusted with the following values for the base case: **τ**=0.01 s, Rmin=0.01 Ohm, and critical current Ic=2000 A.

A three-phase short-circuit has been simulated at Bus 2, with a time duration of 250 ms. In Fig. 3 and Fig. 4 the performance of a step and an exponential SFCL model is compared with the situation without any limiter under increased short-circuit level with respectively instantaneous current and RMS current. Fig. 4 clearly shows that both simplified models limit the short-circuit current to 20 kA. However, the limitation of the step model is faster and thus, the peak short-circuit current is also lower. Nonetheless, in real resistive SFCLs the quenching process will take a limited time.

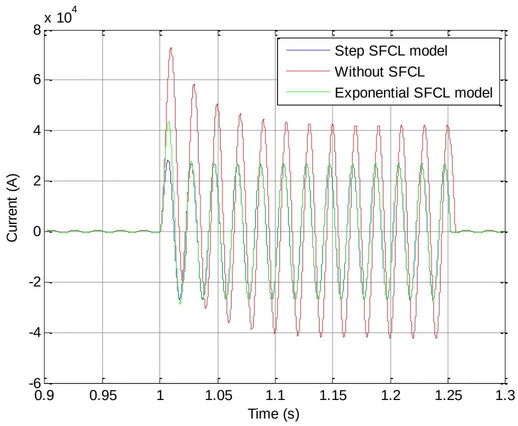

Fig. 3. Performance of simplified SFCL models: instantaneous current

Fig. 5 shows the correlation between the short-circuit current with an exponential SFCL model and the evolution of resistance. Note that the magnitude of resistance has been adjusted in order to allow a straightforward comparison with current. In the simulation base case, the time constant **τ** of the exponential model was set to a usual value in the literature.

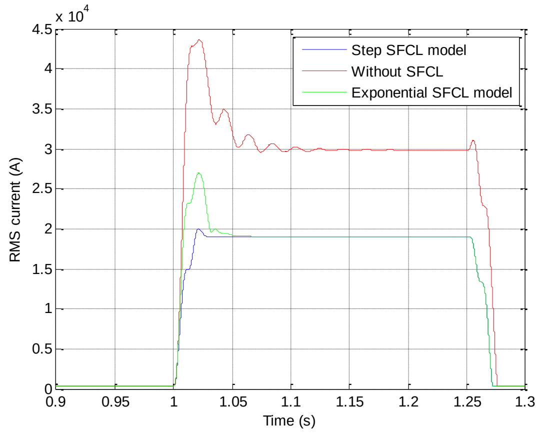

Fig. 4. Performance of simplified SFCL models: RMS current

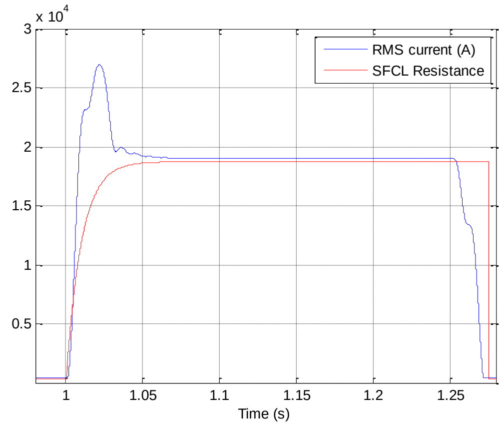

Fig. 5. Comparison of current limitation and resistance evolution in exponential SFCL model

B. Thermo-electric model

The thermo-electric model implemented in this work is based on [17], where a BSCCO superconducting material is considered. Main parameters are summarised in Table I.

Table I. – Main parameters of the thermo-electric model.

Parameter	Value
Superconductor diameter	4 mm
Jc(77 K)	15 MA/m^2
Ec	10^{-4} V/m
E_0	0.1 V/m
α(77 K)	6
β	3
ρ(Tc)	10^{-6} Ohm m^2

The complexity of parameterizing SFCL models increases along with the detail of the model itself. In this case, the thermo-electric model in [17] considers even the cooling process. As a consequence, the parameterization of this model is complex, likewise the design of real installations.

Fig. 6 shows the evolution of resistance in the thermo-electric model. Superconductor length has been varied in order to analyze the effect on resistance.

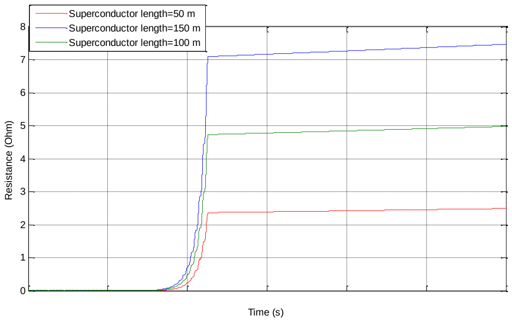

Fig. 6. Resistance evolution in the thermo-electric SFCL model

Based on these results, it can be stated that the superconductor dimensions (e.g. superconductor length in Fig. 6) will be key for adjusting to the necessary limiting capacity, once the superconductor material has been selected and its characteristics are available for modelling.

For the MV radial network under study, a superconductor length of 13 m would be adequate for limiting the short-circuit current to 20 kA.

4. Conclusions

This paper aims to study the challenges related to modelling and parameterization of resistive SFCLs, based on most common approaches: the exponential model and the thermo-electric model. Therefore, latest projects involving resistive SFCLs have been reviewed first, in order to identify current implementation practices. Concurrently with the commercialization of the first SFCLs, different types of simulation models have been introduced in the literature, from simple models to more complex models.

The paper has also studied the issues related to the parameterization of SFCL models. The parameterization of limiter models can be used for studying existing installations, where experimental data of the superconductor behaviour can be available, as well as for analysing the design and implementation of a new SFCL. This paper has focused on the design of a superconducting device for specific current limiting conditions. Thus, key concepts for parameterizing simplified and thermo-electric SFCL models have been introduced.

Finally, the application of a resistive SFCL in a medium voltage grid at 30 kV with radial topology has been simulated with MATLAB Simulink, including an exponential model and a thermo-electric model. Simulation results validate the parameterization approach for the exponential model, whereas the thermo-electric model results into a very complex process. The present paper concludes that the superconductor dimensions (e.g. superconductor length) can be key for adjusting to the necessary limiting capacity, once the superconductor material has been selected and its characteristics are available for modelling.

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