Modelling of (Re)BCO resistive Superconducting Fault Current Limiters with Application to an AC Electric Power Circuit

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Abstract--A thermoelectric model of a resistive-Superconducting Fault Current Limiter (r-ScFCL) is presented. The r-ScFCL consists of a non-inductive coil made of insulated commercially-available YBCO tapes, connected in parallel with a shunt resistance. For this model, a thermal-electrical analogy is utilized to describe the behaviour of the r-ScFCL in adiabatic and liquid nitrogen (LN2) cooling conditions. This model allows predicting the thermal and electrical behaviors of the tape layers over time prior to, during and after a fault occurred. The convective heat transfer is computed for three different curves to span different cooling conditions. Additionally, as the current sharing regime of the superconductor is built in the model, the evolution of the n-value of the power law is also evaluated for the three convective heat transfer cases. Then, using one of the case studies, taken as reference case, the transient stability, the current limiting and the recovery time of the r-ScFCL in a single machine system, connected to an infinite bus, are analyzed when the system is subjected to a three-phase short circuit. It is pointed out that the same r-ScFCL is connected in series with each phase of the three-phase circuit. Parameters such as the length of the superconducting tapes, the number of tapes in parallel and the shunt impedance are adjusted to improve the stability optimizing the operation of the three r-ScFCL as well.

THERMOELECTRIC MODEL

Electrical resistance of the superconducting tape:

$$R_{SC} = \frac{E_C l_{tp}}{I_C}\left(\frac{|i_{SC}|}{I_C}\right)^{n-1}$$

N-value and critical current:

$$n(T_{sc}) = n_0\left(\frac{T_{ref}}{T_{sc}}\right)$$

$$I_C(T_{sc}) = I_{C0}\left(\frac{T_{sc}-T_{ref}}{T_C-T_{ref}}\right)$$

Current sharing:

$$V_C\frac{i_{SC}^n}{I_C} - \frac{R_m R_{sh}}{R_m + N_{tp}R_{sh}}\left(i_t - N_{tp} i_{SC}\right) = 0$$

$$i_t = N_{tp}(i_{SC} + i_m) + i_{sh}$$

Current temperature:

$$\boldsymbol{T}^{new} \cong \left(\boldsymbol{C}^{old} + \Delta t\boldsymbol{G}^{old}\right)^{-1} \ldots$$
$$\ldots\left(\boldsymbol{C}^{old}\boldsymbol{T}^{old} + \Delta t\left[T_{ref}\boldsymbol{G}_b^{old} + \boldsymbol{Q}^{old}\right]\right)$$

Where:

$$\boldsymbol{T}^{new(old)} = \{T_1, \ldots, T_6\}^{new(old)}$$
$$\boldsymbol{Q}^{old} = \{Q_1, \ldots, Q_6\}^{old}$$
$$\boldsymbol{G}_b^{old} = \{G_{01}, 0, \ldots, 0, G_{67}\}^{old}$$
$$\boldsymbol{C}^{old} = \begin{bmatrix} C_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & C_6 \end{bmatrix}^{old}$$
$$\boldsymbol{G}^{old} = \begin{bmatrix} -G_{02} & G_{12} & 0 & \cdots & 0 \\ G_{21} & -G_{13} & G_{23} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & 0 & G_{65} & -G_{57} \end{bmatrix}^{old}_{6X6}$$

$$G_{i,i+1} = 2wl_{tp}/(th_i/k_i + th_{i+1}/k_{i+1})$$
$$G_{i-1,i+1} = G_{i-1,i} + G_{i,i+1}$$
$$G_{01} = \frac{wl_{tp}q(T)}{(T_{ref}-T_1)} \qquad G_{67} = \frac{wl_{tp}q(T)}{(T_{ref}-T_6)}$$

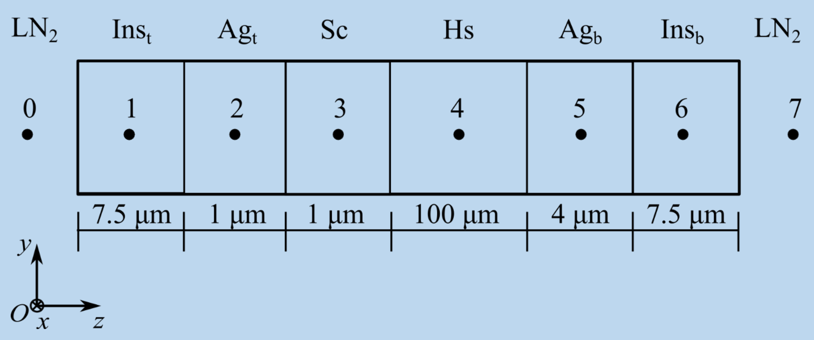

Fig. 1. : Tape layers: insulation (Ins), stabilizer (Sb), silver (Ag), superconductor (Sc) and Hastelloy® (Hs). t and b are the top and bottom layers respectively.

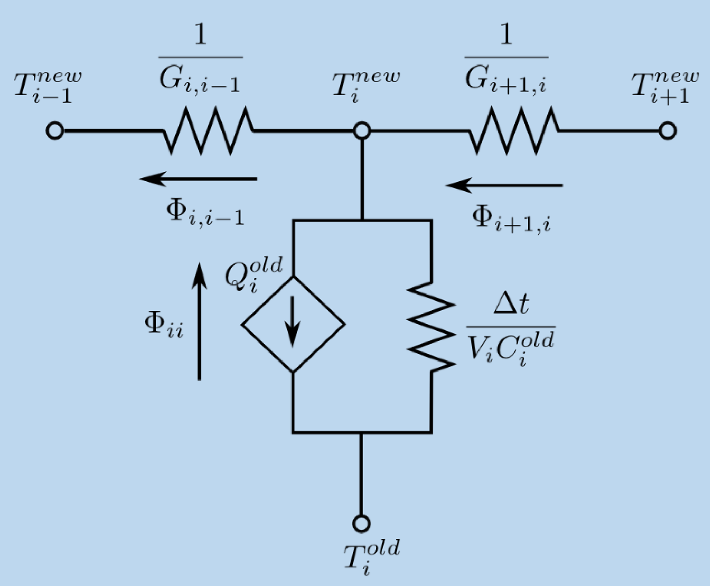

Fig. 2. Thermal lumped parameter model.

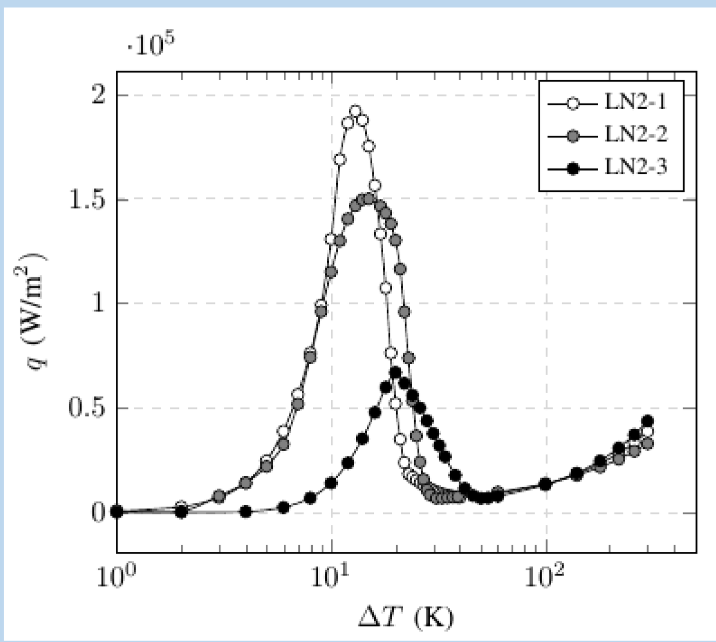

Fig. 3. Heat flux q between the tape surface and the surrounding LN2 at 77 K.

Case of study

The power system under study comprises a synchronous generator, a step up transformer, an infinite bus and a ScFCL model, implemented with SimPowerSystem of Simulink®. The transient behavior of the ScFCL was analyzed, considering four situations: one adiabatic and three non adiabatic with different cooling curves (Fig. 3).

Swing equation: $\frac{d\Delta\omega}{dt} = \frac{1}{2H\omega_0}(P_m - P_e)$, $\quad \int_{\Delta t_f} P_m dt \leq \int_{\Delta t_f} P_e dt$

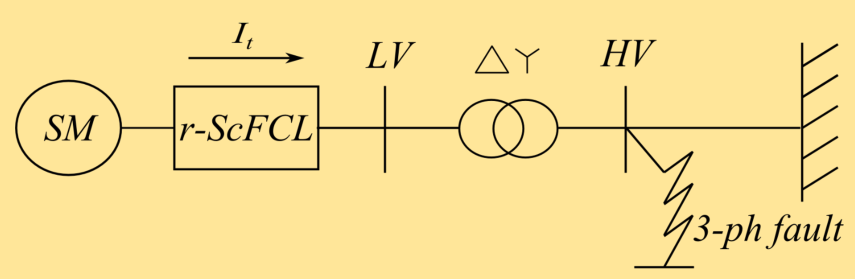

Fig. 4. Three-phase power system

TABLE I. ScFCL parameters

Properties	Value	Unit
Operating temperature	77	K
Number of parallel tapes	40	-
Total length of all the tapes	180	m
Shunt resistance	0.12	Ω

TABLE II. System parameters

Properties	Value	Unit
Generator		
Nominal Power	200	MVA
Nominal voltage	13.8	kV
Inertia coeficient H	3.2	s
Number of pair of poles	2	-
Synchronous speed	276.8	rad/s
Transformer		
Low voltage (LV)	13.8	kV
High voltage (HV)	230	kV
Connection	Delta	Wye
System frequency	60	Hz

Results

The results of the simulations are shown for the phase A of the ScFCL. The fault developed when the current in the phase A is zero.

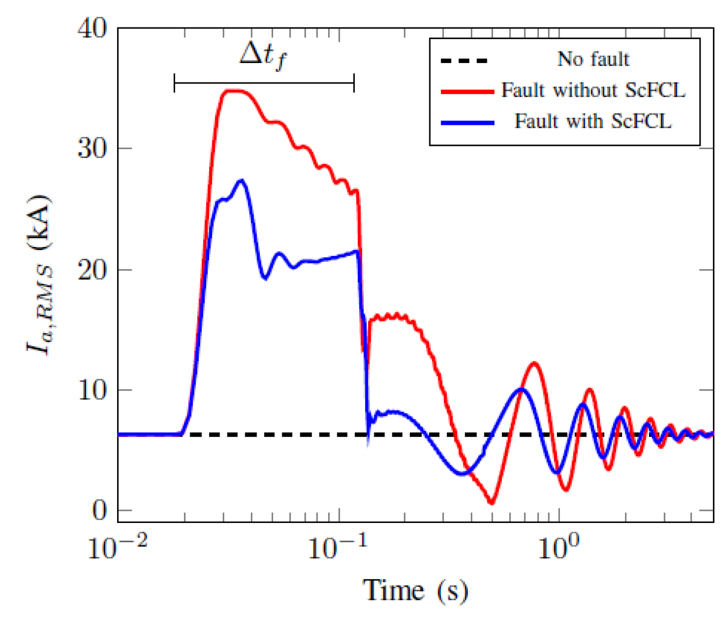

Fig. 5. RMS Current with and without r-ScFCL.

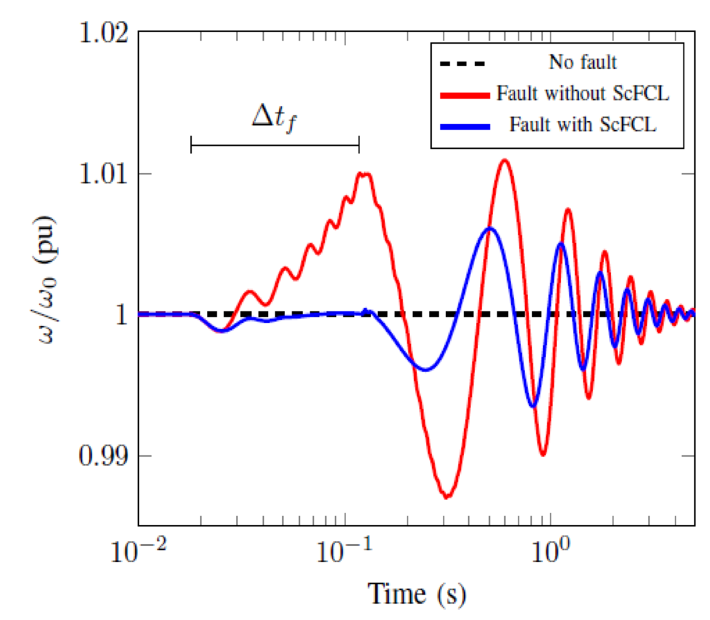

Fig. 6. Rotor speed in pu with and without r-ScFCL.

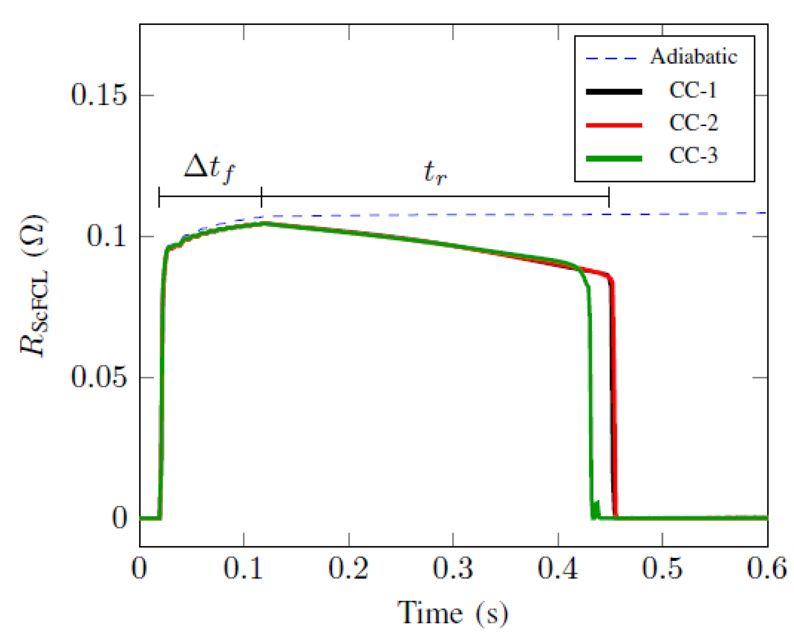

Fig. 7. r-ScFCL resistance as a function of time.

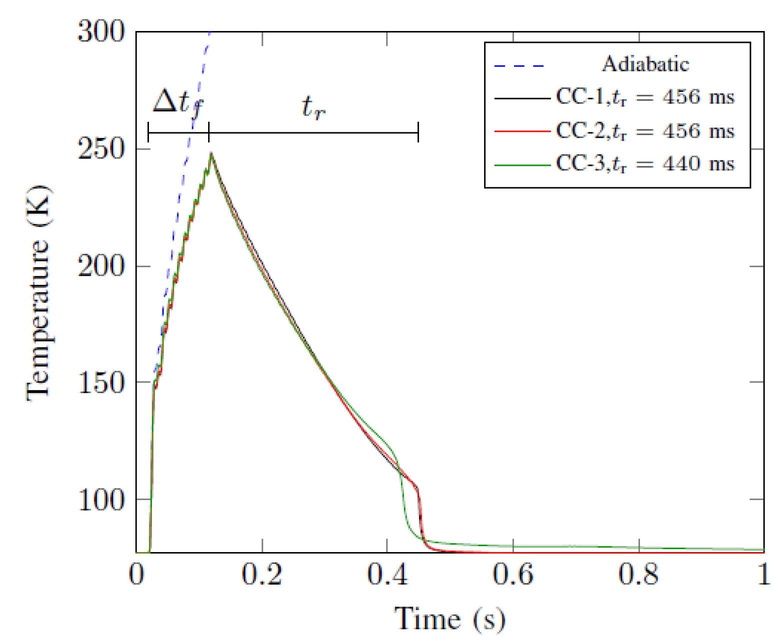

Fig. 8. Temperature of the HTS layer of a single tape.

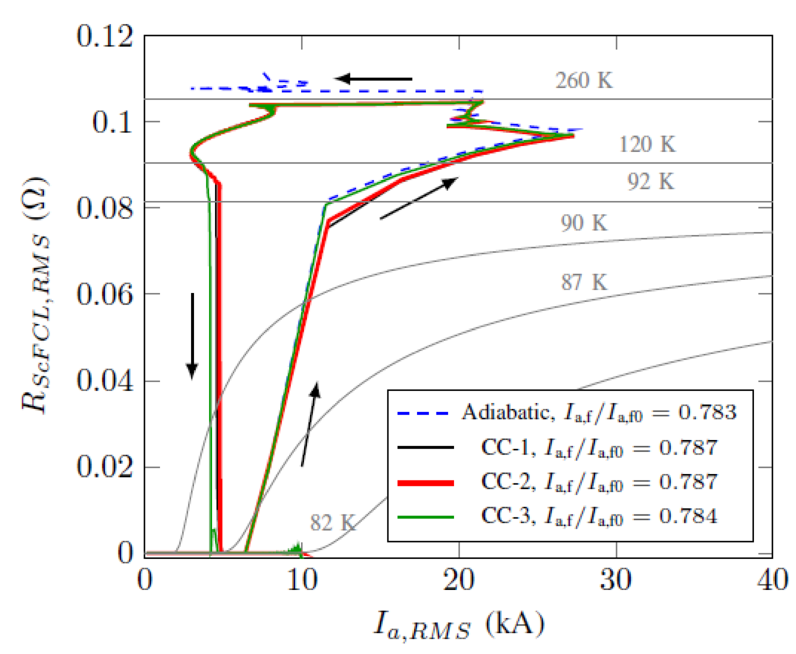

Fig. 9. RMS resistance of r-ScFCL as a function of RMS current.

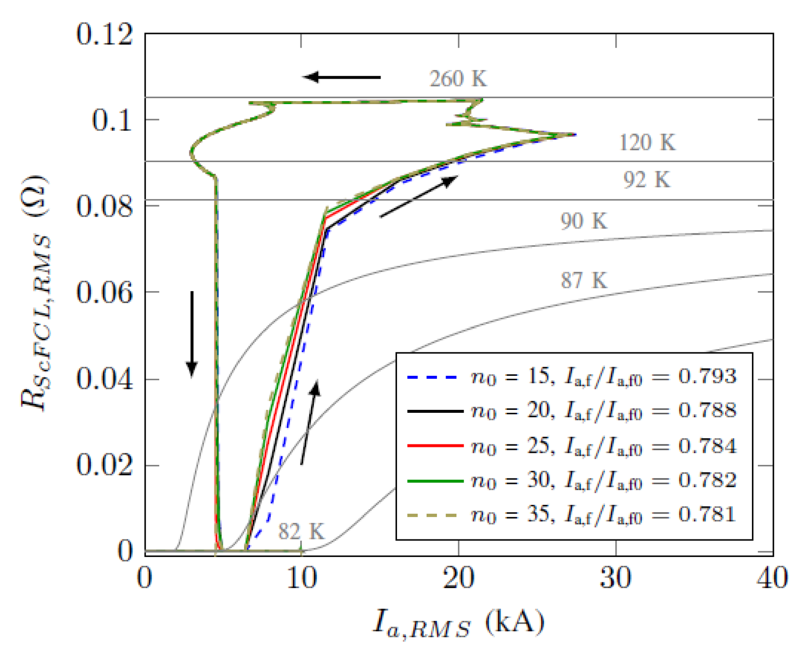

Fig. 10. RMS resistance of r-ScFCL versus the RMS current for different n-values.

Conclusion:

- By optimizing the length of the superconducting tapes, the number of parallel tapes and the shunt resistor, it was possible to achieve self-recovery of the nominal regime without the need for breakers or additional control devices.
- The use of r-ScFCL improves the stability of the synchronous generator, in addition to limit the fault current magnitudes.
- The ScFCL design allows to balance the fault on the three phases, which was not achieved with other ScFCL design.
- The shape of the cooling curve can lead to a quicker onset of the r-ScFCL and a quicker recovery.

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