Simulation model for a novel superconducting fault current limiter

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Abstract. A simulation model for a novel superconducting fault current limiter is presented. The components of the novel fault current limiter are melt cast processed BSCCO 2212 tubes with shunt coils wound around them, which are connected in parallel. The simulation model is based on the electrical and thermal equivalent circuits of a component. A corresponding system of state space differential equations describes these equivalent circuits, which are coupled through several variables. MATLAB is used to solve the state space differential equation system, incorporating the material properties of the bulk BSCCO 2212 as well as the copper coil. Through a comparison of the simulation results and measured data the introduced model is validated. With the simulation model, the design of the components for a fault current limiter can be further improved.

1. Introduction

Several prototypes of resistive superconducting fault current limiters, based on high temperature superconducting material, have already been successfully tested [1]. To achieve a uniform quench all realized resistive concepts up to now apply a metallic shunt, which is continuously contacted to the superconductor. Therefore, rather long material lengths are required, since the maximal allowed electrical field is limited by the heating of the shunt and not by the heating of the superconductor. Especially for high voltage applications, which are the most interesting from the economical and technical point of view, worldwide attempts are made to develop fault current limiters without the metallic shunt. The concept for the novel fault current limiter is based on magnetic field assisted quench propagation [2]. It is similar to the already proposed MFCL concept [3] and utilizes the same superconducting material, but no complex trigger mechanism is needed. The components consist of melt cast processed BSCCO 2212 tubes with copper shunt coils wound around them and connected in parallel. In contrast to the common resistive concepts with the metallic shunt, much higher electrical fields are achieved, thus exploiting the BSCCO 2212 limiting properties much better.

In this contribution a simulation model for this novel fault current limiter concept is presented. Electrical and thermal equivalent circuits for a fault current limiter component are introduced. These, through several variables coupled, equivalent circuits are described by a corresponding system of state space differential equations. The material properties of the superconducting BSCCO 2212 tubes as well as the copper shunt coils are parameterised with analytical expressions. The state space differential equation system is solved using MATLAB. The simulation model is validated through comparing the simulation results with measured data.
2. **Parameterisation of the superconducting material properties**

An empirical correlation for the temperature dependence of the U(I) characteristics of melt cast processed BSCCO 2212 was already proposed in [4]. Nevertheless, for the simulation model the magnetic field as well as the temperature dependences of the U(I) characteristics of the superconducting BSCCO 2212 tubes need to be known. Therefore, these characteristics were measured for different magnetic fields and temperatures [2]. An attempt was made to parameterise the field and temperature dependences with simple analytical expressions. The measured field dependence of the U(I) characteristics at 77 K as well as the parameterised analytical fit is shown in figure 1.

3. **Description of the simulation model**

It was tried to create a simulation model, which is as simple as possible, for the limiting behaviour of the novel fault current limiter concept. Therefore, homogeneous material for superconductor and shunt was assumed. The model is based on the electrical and thermal equivalent circuits for a component shown in figure 2.

Electrically, the superconducting tube is represented through a temperature, magnetic field and current dependent resistance, and the shunt coil is represented through an inductance and a temperature dependent resistance. The changing of the inductance during the limitation due to possible screening effects from the superconductor is not implemented in the model yet. In figure 2 the resistance of the superconductor is shown as a function of the shunt current, which is proportional to the magnetic field supplied by the coil.

Thermally, both, the superconducting tube and the shunt coil, are represented through a temperature dependent heat capacity and a heat source, which takes into account the ohmic losses in the elements. Furthermore, adiabatic heating of the superconductor and the shunt coil is assumed. If the heat conduction through convection to the liquid nitrogen should also be included in the model, the thermal resistances need to be considered in the thermal equivalent circuit. The ambient temperature is set to 77 K, the temperature of liquid nitrogen at atmospheric pressure.

Besides the two equivalent circuits all the connections between the different variables are also shown in figure 2. In addition, the electrical equivalent circuit is extended by a resistance, an inductance and a voltage source. These elements account for the electrical equivalent circuit, which supplies the fault current. Their values are easily obtained through a measurement of the prospective symmetrical fault current, when no fault current limiter component is inserted into the circuit.
As state variables the currents through superconductor and shunt coil and their temperatures are chosen. For the state space differential equation system then results:

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\begin{align*}
\frac{\partial i_{SC}}{\partial t} &= - \left( \frac{R_{SC}}{L_{SH}} + \frac{R + R_{SC}}{L} \right) i_{SC} + \left( \frac{R_{SH}}{L_{SH}} - \frac{R}{L} \right) i_{SH} + \frac{1}{L} u \\
\frac{\partial i_{SH}}{\partial t} &= \frac{R_{SC}}{L_{SH}} i_{SC} - \frac{R_{SH}}{L_{SH}} i_{SH} \\
\frac{\partial T_{SC}}{\partial t} &= \frac{R_{SC}}{C_{th,SC}} i_{SC}^2 \\
\frac{\partial T_{SH}}{\partial t} &= \frac{R_{SH}}{C_{th,SH}} i_{SH}^2
\end{align*}
\]

This state space differential equation system needs to be solved numerically. For each time step the resistances of superconductor and shunt as well as their heat capacities need to be redetermined.

4. Simulation of the limitation behaviour

Tests of the limitation behaviour for five components connected in series were made [2]. In the test setup at the high current facility of I²PS at Bonn, a prospective asymmetric fault current of 80 kA was measured. The measurement of the asymmetric fault current was used to determine the values for source voltage, resistance and inductance of the extended part of the electrical equivalent circuit.

For the simulation of the limiting behaviour of the five components connected in series, the experiment confirmed, that each component behaves identically. Therefore, it was sufficient to do the simulation with just one component and to appropriately adapt the values for the voltage source, resistance and inductance of the extended part of the electrical equivalent circuit. By moderately increasing this resistance the contact and conductor resistances between the components was included.

The state space differential equation system was solved using MATLAB. A comparison of the measured data and the simulation results is displayed in figure 3.
As can be seen in the graphic above, the simulation results match the measured data, especially in the beginning, fairly well. Towards the end of the simulation the measured values of the current are slightly higher than the simulated ones and the measured values for the voltage are slightly lower than the simulated ones.

It needs to be remarked that the simulation model is sensitive regarding the inductance of the shunt and the resistance representing the contacts and conductors between the elements. These calculated values should be verified through further measurements.

5. Conclusion and outlook
A simulation model for a novel fault current limiter concept, which is based on the magnetic field assisted quench propagation, was introduced. The components for this novel fault current limiter consist of melt cast processed BSCCO 2212 tubes with a copper shunt coil wound around them and connected in parallel.

For the simulation model electrical and thermal equivalent circuits of a component as well as the corresponding state space differential equation system was presented. This equation system needs to be solved numerically, and to do this, MATLAB was used.

The limitation behaviour of five fault current limiter components connected in series was simulated. The results match the measured data fairly well. Nevertheless, further improvements need to be done. Especially some of the sensitive values need to be verified. Overall, the simulation model might be used to further improve the design of the fault current limiter components.

References
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