Comparison of different models for superconducting fault current limiters

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1 Introduction

Since the discovery of high temperature superconducting materials in 1986 there has been a dramatic increase in research of superconducting devices for use in electric power systems. A favourable one is the superconducting fault current limiter (SFCL) which has the great advantage of limiting fault currents before their first peak.
There are two different types of SFCL. In resistive ones the superconductor is connected in series with the branch to be protected. It limits the short-circuit current through the quench, which is the transition from the superconducting to the resistive state. For the reduction of thermal stress and to avoid overvoltages parallel elements can be connected. In most cases the superconductor of the inductive SFCLs is magnetically coupled with the branch to be protected. A disadvantage, however, is that they require a large amount of iron. This paper deals with resistive limiters only.
The major effects of using a SFCL in electric power systems are shown in **Fig. 1**. Since fault currents are limited well before their first peak, the application of superconducting fault current limiters results in a considerable reduction of dynamic forces. SFCLs also reduce thermal stress and improve transient stability, which both depend heavily on the short-circuit time.

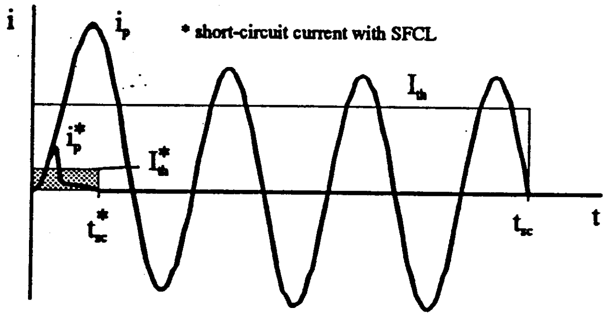

Figure 1: Effects of SFCL

As shown in Fig. 1, SFCLs have a beneficial effect on normal conducting power systems. Other superconducting devices have to be combined with SFCLs to protect them from the quench. Circuit breakers are not suitable for the protection of superconducting devices because they can't limit the short-circuit current. They break the short-circuit current after a few current zeros. Fuses that are able to limit a short-circuit current at its first rise have to be replaced after their release.
The aim of this paper is to show and compare suitable models for SFCL. This is important for the development and the rating of SFCL and for the study of the transients of electric power systems.
The least complicated model describes the behaviour of a SFCL with a simple time dependent resistance. A more accurate one is based on Gorter and Casimir's two-fluid theory of superconductivity from 1934 [4]. The most sophisticated model uses a finite difference method (FDM) in order to simulate the behaviour of a SFCL [5]. The calculations in this report are restricted to $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO) as superconducting material.

2 Different models for SFCL

2.1 Nonlinear-resistance model

A very simple way of simulating the electrical behaviour of SFCL is to represent the resistance as shown in **Fig. 2**. Immediately after the short-circuit the resistance is assumed to be zero. The delay time results from the time needed to reach the critical current and the critical temperature of the SFCL. It depends very much on the load conditions and the time when the short-circuit occurs. Since the quench takes place very quickly (t_{quench} < 1 ms) it is assumed that the resistance builds up in a linear way as time proceeds. The SFCL is represented by a constant resistance after the quench.

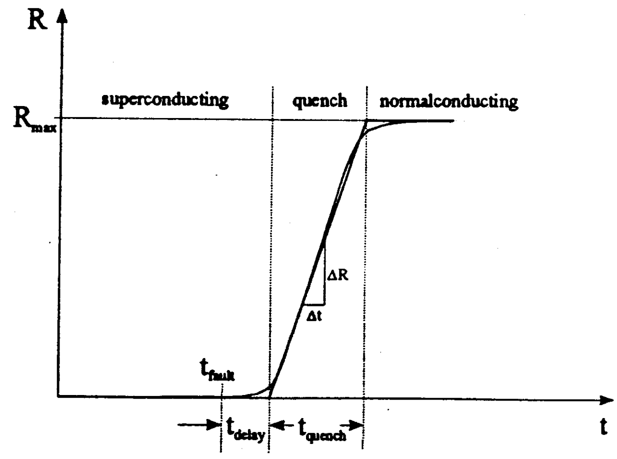

Figure 2: Nonlinear-resistance model

The benefit of this model is its easy implementation because only a few parameters (t_{fault}, t_{delay}, t_{quench}, R_{max}) determine the characteristics of the resistance.

2.2 Two-fluid model

The electrical equivalent to the two-fluid model (**Fig. 3a**) is based on Gorter and Casimir's two-fluid theory of superconductivity from 1934 [4]. It gives a phenomenological description of the behaviour of the superconductor. The electrical equivalent is divided into two parallel branches. The total current is the sum of the supercurrent i_s and the normal current i_n. The supercurrent is zero if the temperature is above the critical temperature. In this case the current from the current source is zero too and the switch, as shown in Fig. 3a, is open.

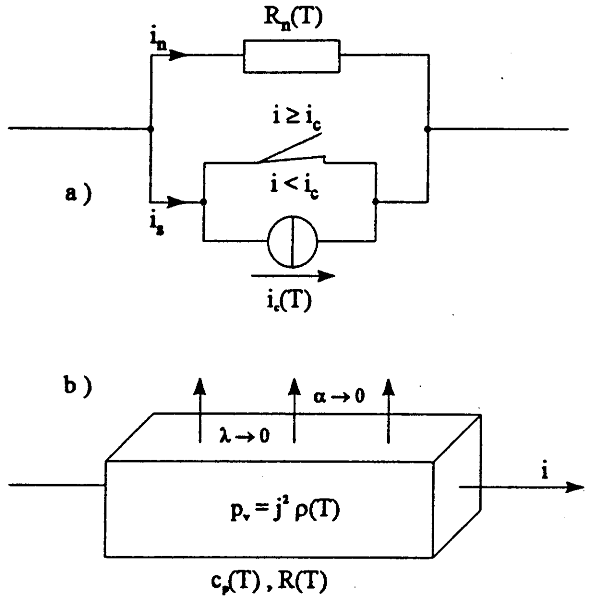

Figure 3: a) Electrical equivalent
b) Thermal representation

The resistance of a superconductor below the critical temperature is near zero as long as the critical current which depends on the temperature is not reached. In this case the switch remains closed and the resistance and the current source are short-circuited.

As soon as the current density in the superconductor reaches the critical current density the switch opens. Then the normal current is no longer zero and energy is dissipated inside the resistance. This leads to an increasing temperature, an increasing resistance and a decreasing critical current. The critical current is zero if the critical temperature is reached. The temperature dependence of the specific resistance, the heat capacity and the critical current are described in [5][7]. This model neglects the influence of external magnetic fields.

For the calculation of the temperature and temperature dependent values there is a need for a thermal equivalent (**Fig. 3b**). To keep the model simple the following assumptions were made. The system is adiabatic ($\alpha = 0$), so that there is no heat transfer to the cooling fluid. Furthermore, the thermal conductivity λ is that low that the heat conduction in the superconductor can be neglected. This leads to the heat equation in the form:

$$c_p \, \Gamma \frac{dT}{dt} = p_v = j^2 \rho \qquad (1)$$

2.3 FDM model

BSCCO's resistivity depends on the current density and the temperature [5]. The heat conduction, the heat transfer coefficient and the specific heat are temperature dependent, too [5].

The description of the thermal behaviour is based on the three-dimensional unsteady heat equation with heat sources and variable material properties. The differential equation is as follows:

$$c_p \Gamma \frac{dT}{dt} = \frac{\delta}{\delta x}\left(\lambda \frac{\delta T}{\delta x}\right) + \frac{\delta}{\delta y}\left(\lambda \frac{\delta T}{\delta y}\right) + \frac{\delta}{\delta z}\left(\lambda \frac{\delta T}{\delta z}\right) + j^2 \rho \qquad (2)$$

For reasons of simplification it is assumed that the length of the superconductor is very big in relation to the size of the cross-section. Therefore the terms which contain z can be neglected. The solution of this equation can be iterated by the finite difference method (**Fig.4**). For its application the cross-section is divided into discrete areas in which the properties are assumed to be constant. The derivatives are substituted by the gradient function.

The thermal and electrical solution have to be combined each time step. Because of the temperature and current dependence of the resistivity the equations have to be solved by iteration. The difference equation for the electrical circuit is solved by a Runge Kutta method. A more detailed description of this model is given in [5].

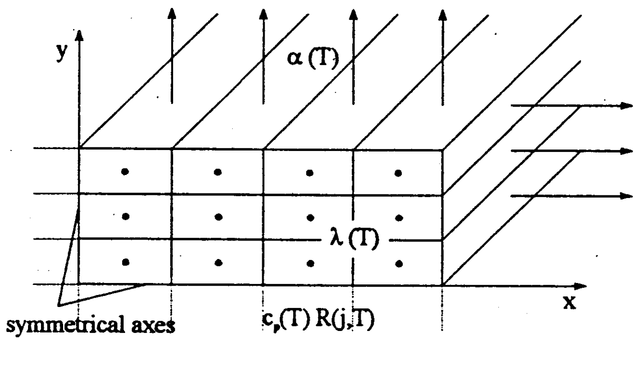

Figure 4: Finite difference method

In contrast to the two-fluid model, one gets the temperature, current and resistance distribution considering the whole cross-section. This model also considers the cooling power. Therefore it is possible to calculate recovery times after a quench.

3 Comparison of SFCL models

The test circuit used for calculations is shown in **Fig. 5**. It is assumed that there is no load during the steady state and that the short-circuit occurs at the voltage zero. The calculations are limited to the first swing, because the maximum short-circuit current, which is responsible for the mechanical stress, occurs during this time span. The overvoltages produced by the quench take place during the first swing, too.

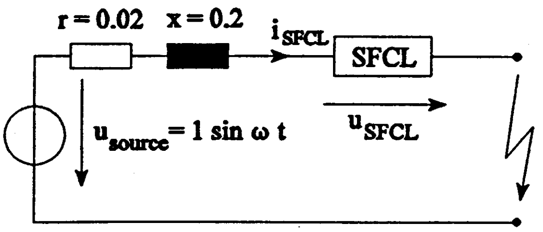

Figure 5: Limiter test circuit

A typical graph of voltage and current computed with the FDM model in the case of a short-circuit within the test circuit (Fig.5) is shown in **Fig.6**. The unlimited current would rise to about 9 times the value of the rated current. Shortly after reaching the critical current of the superconductor, the critical temperature is exceeded. This results in a fast and massive rise of the resistance which limits the current effectively. A great overvoltage results from the fast change of the current. By parallel elements this can be kept within its permissible limits.

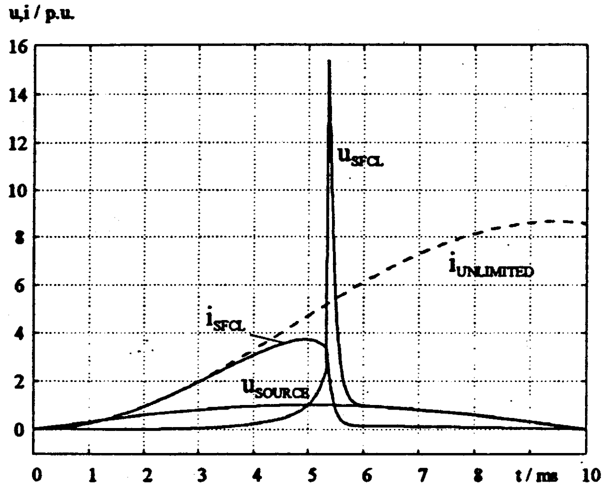

Figure 6: Graph of voltage and current

The following diagrams compare the different SFCL models. The graph of the resistance of the nonlinear resistance model has been found from the graph of the resistance of the FDM model. The rise was determined from the 10%- and 90%-values of the resistance which builds up during the first current zero.

Fig.7 shows the graphs of current for all models during the first 10 ms after the fault. The nonlinear resistance model calculates the largest maximum short-circuit current. The reason is the long delay time which results from the graph of resistance (**Fig.9**). In contrast to the other models, the nonlinear resistance model assumes no resistance until the quench. In reality there is a non-neglectable resistance shortly after reaching the critical current. The difference between the two-fluid model and the FDM model results from the modelling of the resistance before the critical temperature is reached.

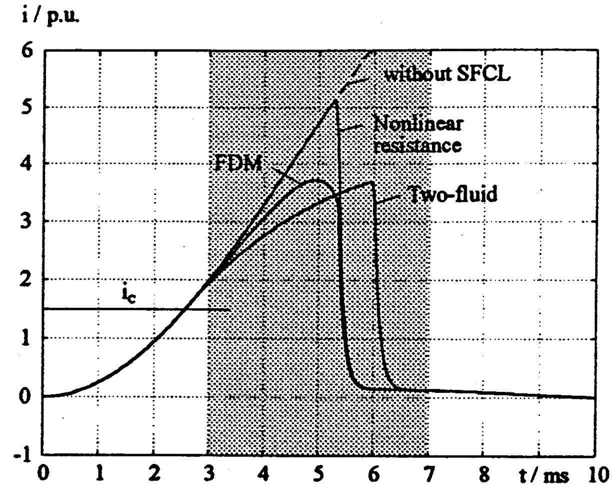

Figure 7: Comparison of current curves (i_{SFCL})

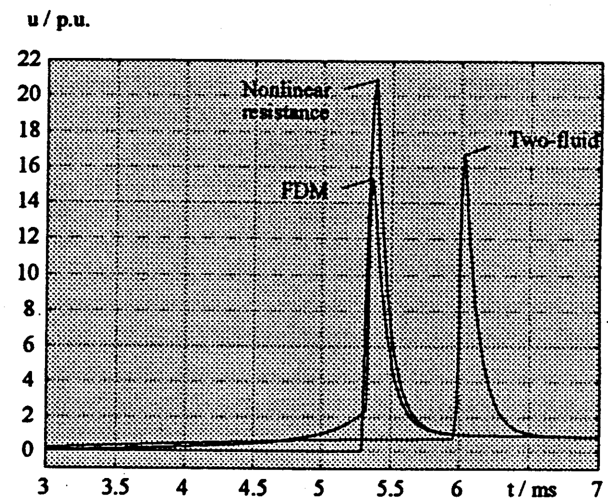

Figure 8: Comparison of voltage curves (u_{SFCL})

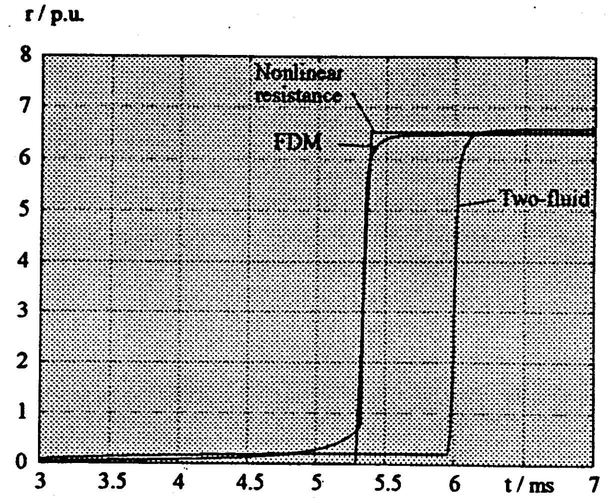

Figure 9: Comparison of resistance curves (R_{SFCL})

The two-fluid model calculates a higher total resistance than the FDM model in the time span shortly after reaching the critical current. This leads to a lower current and lower dissipated energy, so that the sharp increase in resistance is delayed. As shown in **Fig.8** the nonlinear resistance model also calculates the highest overvoltage. This is because the quench takes place at higher currents in this model. Similar results were obtained with varying short-circuit times and other load conditions, too.
All calculations in this paper were carried out with the computation software MATLAB. The comparison of the simulation times showed that, by using the same time steps, the two-fluid model needed about twice and the FDM model even thirty times the computation time compared to the nonlinear resistance model.

4 Summary

For the calculation and design of electric power systems with SFCL simulation models are needed that are able to simulate their electrical behaviour. This paper shows and compares three different models of resistive SFCL.
The proposed models differ in structure, expenditure and accuracy. The most accurate and also the most sophisticated is the FDM model. The results obtained with the two-fluid model vary considerably compared to the FDM's. This results from the differences in modelling of the resistance before the critical temperature is reached. The two-fluid model neglects that the resistance depends on the current density. The combination of a controlled current source with a switch compensates for this. This delays the sharp increase in resistance.
The application of the most basic model presumes the need of an accurate graph of resistance that can be obtained from the other models or from measurements. It is suitable for quantitative simulations and has only a low degree of complexity.
The fairly large current changes during the current limitation result in high overvoltages at the inductivity. These occur with inverse signs at the SFCL, too.

5 Symbols

c	specific heat
i	current
i_p	peak short-circuit current
I_{th}	thermal current
j	current density
p	heat source
R, r	resistance
t	time
t_{sc}	short-circuit time
T	temperature
u	voltage
x	reactance
α	heat transfer coefficient
λ	thermal conductivity
Γ	density
ρ	resistivity
ω	frequency in sec^{-1}

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