Lumped Network Model of a Resistive Type High T_c fault current limiter for transient investigations

Ricard Petranovic and Amir M. Miri

Universität Karlsruhe, Institut für Elektroenergiesysteme und Hochspannungstechnik, Engesserstrasse 11, D-76128 Karlsruhe, Germany (email: ricard@ieh.uni-karlsruhe.de)

***Abstract* – In general, simulations of superconducting fault current limiters (SFCL) include the thermal- and electrical-behaviour of the limiter. Thermal properties deal with resistive heating caused by AC losses, increasing resistivity, etc. Electrical behaviour includes the U-I or E-J characteristics which are specific for every type of superconductor. This type of simulations is mainly made to predict the performance of the limiter in the electric power system if a short circuit occurs. The rise time of this signals is in the region of milliseconds.**

Signals with a smaller rise time can cause high voltage stresses if the frequency of the signal corresponds to the natural frequencies of the winding system. In this case resonance excitations are caused in the windings of the limiter, which can lead to insulation faults and therefore have to be considered during the design. High voltage stresses in electric power systems can be caused by lightning strikes, disconnecting operations or system disturbances. The rise times of the initiated travelling waves are in the range of ms to ns and correspond to frequencies in the range of kHz to several MHz.

In this paper the transient behaviour of a high T_c resistive SFCL made of BSCCO 2212 tubes is modelled and evaluated. A lumped network model of a 15 MVA limiter is established and simulations in both, time- and frequency-domain are performed. The model includes the frequency dependence of the resistance R, being caused by the skineffect and the frequency dependence of the inductance L.

Keywords – Transient Analysis, Modeling, Superconducting Fault Current Limiter, PSpice

I. INTRODUCTION

The design of superconducting equipment, such as the SFCL, includes thermal and electrical properties of the material [1]. Thermal properties deal with the resistive heating due to AC losses during normal operation and especially for the SFCL an increasing resistance due to fault current limitation. Electrical properties often deal with critical current density J_c and critical electrical field strength E_c. An important fact being not considered sufficiently is the coordination of insulation to withstand overvoltages caused by resonance excitations.

Electrical equipment can be subject to various kinds of high voltage stresses caused by lightning strikes, disconnecting operations or system disturbances. The rise times of the initiated travelling waves are in the range of ms to ns and correspond to frequencies in the range of kHz to several MHz. If the dominating frequency of a signal corresponds to the natural frequency of the winding system, resonant oscillations are excited. These cause high voltage stresses in the windings of the limiter, which can lead to insulation faults, and therefore have to be considered in the design of the limiter. If electrical equipment is deployed in electric power networks in Europe, it has to withstand the demands of the European standard IEC 600056. This standard includes for equipment used in the 10 kV voltage level the test with a 1.2/50 µs lightning impulse voltage with 75 kV peak value, a power-frequency withstand voltage with 28 kV r.m.s. value and a 30/300 µs lightning stroke current with 30 kA peak value.

To investigate the transient behaviour of the limiter a lumped network model has been developed, allowing us to calculate voltages and currents in all windings.

II. LIMITER

There are two main types of superconducting fault current limiters being used for current limitation. One is the inductive- or shielded core type and the other a resistive type [2].

The limiter being modelled in this work is a resistive-type limiter made of melt cast processed BSCCO 2212 tubes which have already been tested successfully [3]. Fig. 1. shows the design of one module.

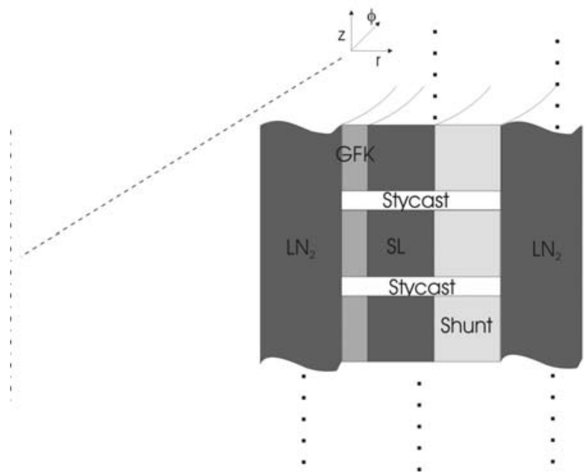

Fig. 1 Construction of a tube of the limiter.

To prevent an overheating during limitation, the superconductor (SC) has a Copper Nickel shunt parallel, which will carry the current as soon as the superconductor becomes normal conducting. To increase the mechanical stability epoxy-glass resin (ER) has been added to the inside of a module.

The superconductor is a high T_C superconductor and is operated at 65 K to increase the critical current density $\boldsymbol{J_C}$. To reduce the magnetic field $\boldsymbol{B}$ and the forces due to the high currents during limitation the limiter is made as a bifilar wound coil. The main parameters of one module of the limiter are shown in Table 1.

Table I Parameters of BSCCO 2212 limiter at T=65K

Critical temperature T_c	92K
Critical current density	3600A/cm^2
Conductor length	5.4 m
Cross section	0.24 cm^2

For the application of the limiter in the 10 kV grid, thirty modules per phase will have to be connected in series. Thus, one phase of the complete SFCL will have a length of 162 m approximately.

III. Lumped Network Model of the SFCL

To simulate the resonant behaviour of the limiter, electric and magnetic fields are assigned to an electric network consisting of lumped elements, Fig. 2.

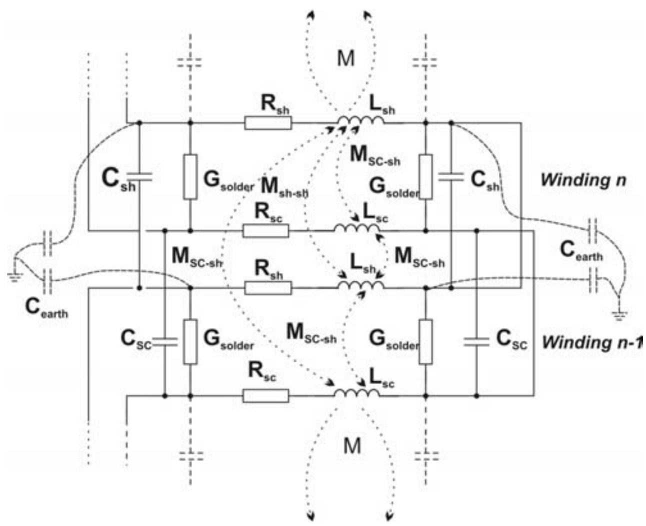

Fig. 2 Section of a limiter winding with the complete electric- and magnetic coupling.

To use lumped elements, the conductor has to be considered as *electrically short* [4]. The distinction between *electrically short* and *electrically long* lines is possible either in the time- or in the frequency domain. In the time domain, the rise time of a signal has to be smaller than the travelling time τ. Otherwise the currents and voltages have to be described with partial differential equations, since they are both, time- and location dependent.

Each winding turn of a module was modeled by a single discrete inductance L in series with a resistance R, representing the magnetic self-field and the ohmic-losses. The mutual inductance M represents the coupling between each single winding of the limiter.

The two branches in parallel in each winding correspond to the superconductor and the copper-nickel-shunt. The conductance G between superconductor and shunt represents the contact resistance of the solder. Capacitance elements C account for the electric field between adjoining windings and between windings and the grounded cryostat walls.

IV. Reduced Model

To enable a computation of the complete limiter with 30 modules in series, several windings of a module have been combined to one branch in the model. Therefore, the inductances, resistances, capacitances and couplings had to be summarized. An appropriate number of windings has to be found as a compromise between computation time and accuracy of the model. In our case five windings have been combined to one branch. The amount of parts with and without reduction is shown in Table 2

Table II Number of elements for regular and reduced model

Parts	Regular Model	Reduced Model
Capacitances	4170	1392
Inductances	2160	480
Resistances	4320	960
Couplings	76680	3600

V. Determining the Lumped Elements

A. Resistance

The DC-impedance (R_{DC}) for the CuNi shunt R_{sh} was calculated with the resistivity of CuNi for 65K. However, for transient investigations the AC resistance of the CuNi shunt differs from the DC value because of the skin effect. With increasing frequency the resistance will increase since the current is displaced towards the outer border of the conductor. The resistance of the superconductor R_{SC} of the lumped network model is set to the normal state resistance near T_c to investigate the behaviour of a already quenched conductor.

An analytical solution is feasible only for simple wires with circular cross-section. Since the conductor in this work has a rectangular surface, a two dimensional axis-symmetric FE model of one winding was created and Fig. 3 shows the distribution of the current density for various frequencies.

Based on $P = UI$ and $R = P/I^2$ the resistance of the CuNi shunt can be calculated with the formula

$$R = \frac{\frac{1}{\sigma}\int_V J^2 dV}{\left(\int_A J dA\right)^2} \tag{1}$$

where σ stands for the conductivity, J for the current density, V for the Volume and A for the surface of the conductor from Fig. 3. Fig. 4 shows the frequency dependence of the resistance caused by the self-field of the current. It can be seen that the AC resistance is twelve times the DC value for a frequency of 8 MHz.

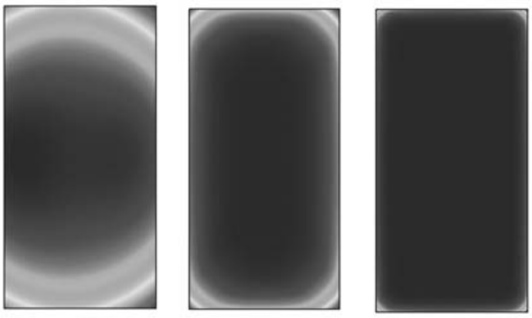

Fig. 3 Distribution of current density for 1 kHz (left) , 1MHz (middle) and 9 MHz (right), showing the current density increasing on the conductor border as the frequency increases.

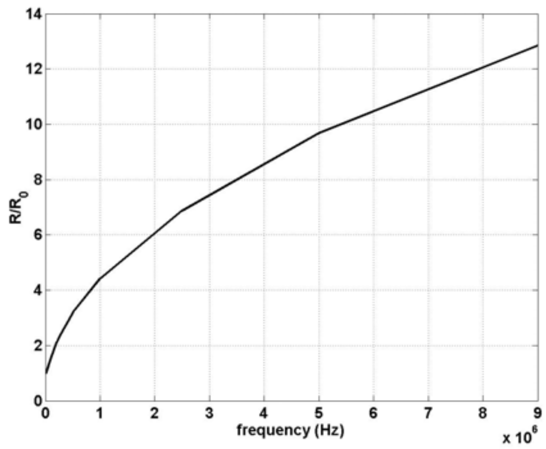

Fig. 4 Frequency dependence of the Copper-Nickel shunt resistance.

B. Self- and Mutual Inductance

The DC value for the self inductance of a single winding was also calculated with a two dimensional axisymmetric FE model. The inductance can be devided in an inner inductance L_i coming from the component of the magnetic field strength H in the conductor and an outer conductance L_o from H outside of the conductor. Because of the above mentioned skin effect, L_i will be also frequency dependent. Fig. 5 shows the frequency dependence of the inner inductance L_i , the constant value for the outer conductance L_o and the total conductance L_{total}.

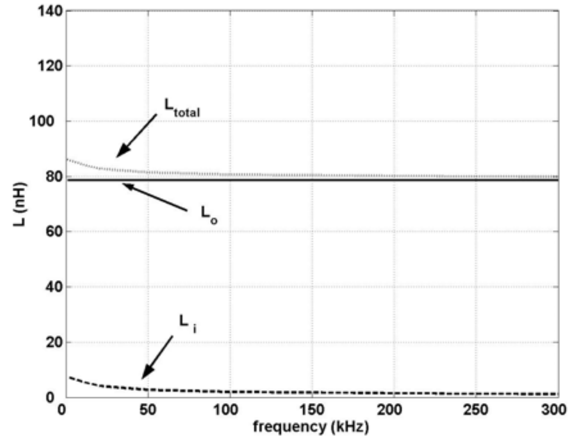

Fig. 5 Frequency dependence of the Inductance L of one winding.

The values for the mutual inductance M_{ik} of two coils i and k close together have been calculated with EFFI [5], which is based on Biot-Savart's Law.

The general formula to calculate the mutual inductance of two coils is

$$M_{ik} = \frac{\mu}{4\pi}\frac{1}{I_1 I_2}\int_{V_1}\int_{V_2}\frac{\mathbf{J}_1(\mathbf{r})\mathbf{J}_2(\mathbf{r'})}{|\mathbf{r}-\mathbf{r'}|}dV_1 dV_2\,, \tag{2}$$

where I_1 and I_2 are the currents through coil 1 and coil 2, respectively. $\mathbf{J_1}$ and $\mathbf{J_2}$ are the corresponding current densities and $|\mathbf{r}-\mathbf{r'}|$ is the distance between the two coils with volumes V_1 and V_2, respectively. The mutual inductance of more distant windings has been calculated with [6]

C. Capacitances

All capacitances of the lumped network were considered to be constant for the investigated frequency range. The capacitances between single windings of a module were obtained with simple analytical formulae.

The coupling capacitances between adjacent windings of different modules and the grounded cryostat were obtained with a two dimensional FE model of the limiter, Fig. 6.

One can see one phase of the limiter with the thirty modules and the grounded cryostat. Brighter regions have a higher magnitude of electrical field strength. The capacitance was determined with the following formulae

$$W = \frac{1}{2}\int_{Volume}\mathbf{E}\cdot\mathbf{D}\cdot dV \tag{3}$$

and

$$W = \frac{1}{2} C U^2 , \quad (4)$$

where W denotes the electric energy of the field, **E** the electric field, **D** the displacement current density, C the capacity and U the voltage.

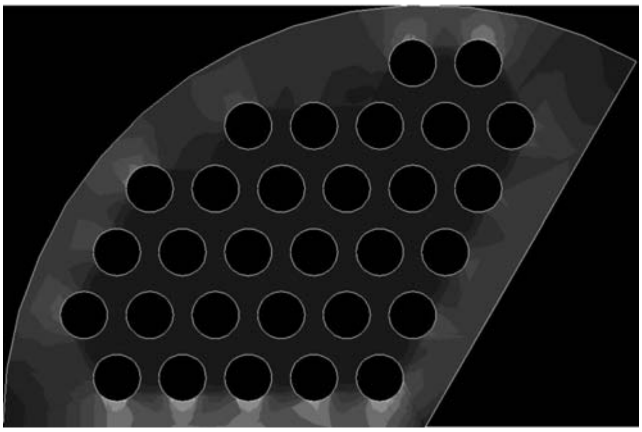

Fig. 6 2D FE model with field distribution of the limiter

VI. Model and Simulation

To investigate the transient behaviour of the limiter, a PSpice® model, consisting of thirty modules in series, with the values from section IV has been developed. Fig. 7 shows the block diagram of the limiter.

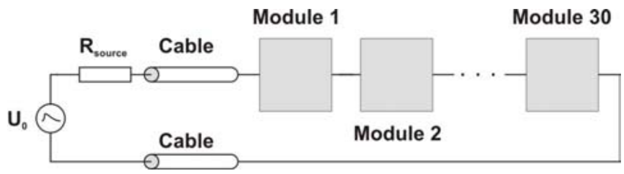

Fig. 7 Block diagram of the limiter.

The equivalent network, shown in Fig. 2, is implemented in each module with the reductions from chapter IV. The circuit consists of a voltage source with a 30 Ω impedance, a cable with a characteristic impedance of 30 Ω, the limiter with thirty modules followed by another 30 Ω cable. The circuit was used for time domain analysis. The 30 Ω impedance is used to terminate the cable and thus not to obtain reflections of the signal.

The following simulations have been performed with a quenched superconductor with a resistivity near T_C. This case represents the worst case scenario where a surge propagates into the SFCL after a limitation.

In general, a circuit with capacitances and inductances represents a resonant circuit. High overvoltages can occur, if natural frequencies of the circuit are excited. To determine these frequencies, a frequency domain analysis with 1 V peak voltage and a frequency range from 1Hz to 100 MHz was performed with a circuit without cables and resistance and the results are shown in Fig. 8. One can see the simulated per unit voltage between two windings of module 1. The results show a 15.5 times higher voltage between the windings at 10 MHz as compared to the DC value U_0.

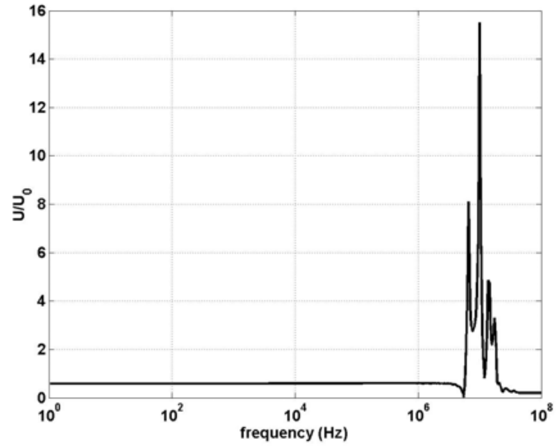

Fig. 8 P.U. Voltage between windings of module one.

As mentioned in the introduction, the limiter has to withstand certain tests defined by the European standard IEC 600056. In this work the model is tested with the 1.2/50 µs lightning impulse voltage. To test the insulation a impulse of 40 kV peak and a rise time of 0.1 µs is applied. Since the frequency of 50 Hz leads to a homogeneous distribution, the effects of the power-frequency withstand voltage are not investigated.

Fig. 9 shows the results of the simulation with the 1.2/50 µs lightning impulse voltage with 150 kV crest value.

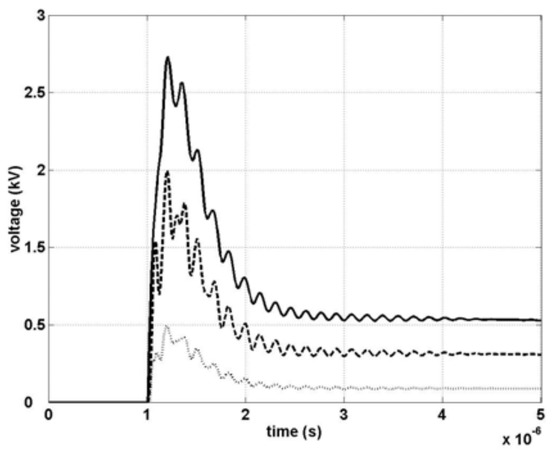

Fig. 9 Voltages between windings of module one.

The voltage is then divided between R_{source} and the cable to the desired withstand voltage of 75 kV. One can see on

Fig. 9 that no overvoltages occur due to resonant excitations. The voltage is distributed homogeneously over the thirty modules, hence approximately 2.1 kV are between in- and output of one module. The dotted- and dashed lines represent the voltage between windings 4 and 5 and between 7 and 8 of the same module.

The first harmonic of this impulse is 208 kHz and according to Fig. 6 no resonance is expected for this frequency.

A second simulation was performed with a impulse of 40 kV peak and a rise time of 0.1 µs. The results are shown in Fig. 10. According to the number of modules a peak voltage of 1.33 kV has to be expected. However, a peak of 2 kV can be observed being caused by resonance excitations. Since the value does not exceed the breakdown strength of the liquid Nitrogen between two windings, no counteractive measures have to be taken into account.

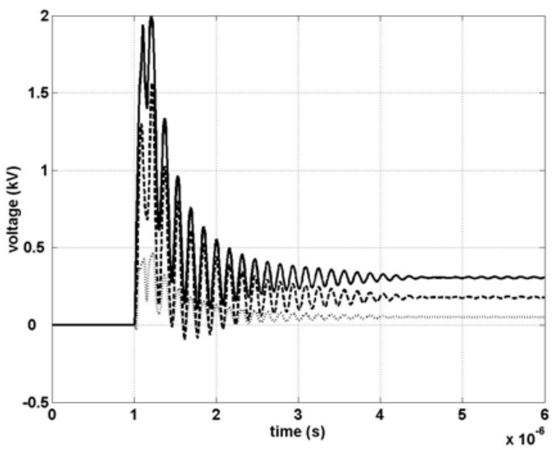

Fig. 10 Voltages between windings of module one

VII. CONCLUSIONS

The transient behaviour of a high T_c resistive superconducting 10 MVA limiter (SFCL) made of 30 series connected Bi-2212 tubes was investigated. Therefore a lumped network model of the limiter was implemented in Pspice. The parameters of the model (R, L, C) are obtained with both, analytical formulae and FE models. Frequency dependence of the resistance R and the inner inductance L_i is determined and included in the model. To enable a computation of the model the number of elements is reduced. To determine the resonance frequencies of the limiter a frequency domain analysis is performed. After frequency domain analysis a time domain analysis is performed with voltages required from the European standard IEC 600056. No overvoltages due to resonance excitations can be observed.

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