Three Phase superconductor fault current limiter
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Abstract - Fault Current Limiter concepts are based on high temperature superconductors. The application of superconductors on current limitation is due to the normal resistive behaviour presented once the critical values related to temperature, current density or magnetic field are broken. This work first objective is to develop and validate a model equation that represents the limitation behaviour of the FCL. In order to do so, temperature data must be acquired and analysed. No results were obtained due to precision of the applied sensor. The second objective is to adapt the FCL to a three phase system. On this rectifier was used in order to maintain the same amount of superconducting material. Asymmetrical network functioning was studied and the fault currents dimensioned. At last, the three phase limitation system was successful in every type of defect and the limitation levels were the same as the mono phase assembly maintaining the amount of super conducting material.

Index Terms—Superconductors, Fault currents, Three phase system, rectifier.

I. NOMENCLATURE
HTS – High Temperature Superconductors
K – Degrees Kelvin
R – Resistance
J – Current density
P – Power
V – Voltage

II. INTRODUCTION

It is obvious that nowadays the electrical network’s growth is a direct function of current and future social requirements, society has become fully dependent on luxuries such as light, TV’s, Stereos, microwaves, Computers, DVD players, Playstation and all other electrical devices indispensable to urban survival and entertainment. The need for a greater, more efficient and uninterrupted electric supply is a topic very much debated and studied throughout the world.

Considering the fore mentioned, the need arises for the development of an alternative fault protection device that maintains constant energy supply. The main objective of this project is to meet this need. It acts during a fault current, limiting the effects of the fluctuation without opening the circuit. This system is based on superconducting material, whose proprieties are presented in the text. This work has basically two objectives:

1 - Characterize the thermal and resistive behavior, and validate the system model;
2 - Implement the fault current limiter in a three phase system.

III. System Model

The first purpose of this project is to characterize and modulate the resistive behavior of the BSCCO superconducting material. To begin we must first analyze the
properties of superconducting materials. In brief, we can say that this kind of material under very low temperatures of about 70K expels all magnetic field forces from its surface, the magnetic field equals the magnetizations forces. This type of material is defined by three criteria: current density, magnetic field and temperature. The way they co-relate is defined by critical values of each field, therefore if one of the critical values is exceeded the material will no longer present itself with superconducting properties and behave as a normal resistive conductor, diffusing energy at its terminals. There are two types of material:

- The first type of material is defined by an abrupt transition between the superconducting state and the resistive conductor state, and very low temperature to achieve superconducting state.
- The second type of material has a gradual transition between states and reaches superconducting status at higher temperatures.

Based on previous studies referenced [1] it is known that resistivity depends mostly on temperature and current density, its also known that temperature varies according to the current.

Having established these concepts, it is now necessary to develop and define a thermal model that provides temperature information, since it’s one of the factors that lead to the transition between states. The analysis made in passed years focused precisely on these factors. They basically observed the voltage across the superconducting material during the transition between states provoked by variation of the temperature above critical levels, by pulling the material out of the recipient, so no critical current was achieved. In resume of the experiment it was verified that there where two time steps: the first one is quick and is related to the break of the critical temperature; the second is slow and associated with the normal temperature rise of each material when a current goes through it. In conclusion the resistive behavior of the superconducting material was divided in two parts:

- The first corresponds to superconducting state, when the current passing through the material is below it’s critical value, and therefore no resistance;
- The second, when the current passing through the material is above critical value, a resistive behavior is characterized by a fixed resistive value and a temperature depending factor (Eq. 1.1).

\[
R = \begin{cases} 
0 & \text{se } J < J_{\text{Crítico}} \\
R_0 + \beta \Delta T & \text{se } J > J_{\text{Crítico}} 
\end{cases}
\]  

(Eq. 1.1)

The idea is to create an experiment that provides information regarding all factors of the thermal model. Having that in mind an experiment was elaborated inserting a thermometer attached to the superconducting material in order to obtain temperature values on the surface of the material, also recording voltage and current values. Although the transition between
superconducting and resistive state was observed from the voltage and current values, no temperature transition was observed. The causes for this effect rely on two factors:

- The calibration curve for the thermometer, since it is more suitable for temperature ranges up to 40K and the working temperature of liquid nitrogen is 70K;
- The fact that the body of the thermometer was more exposed to the liquid nitrogen than to the material itself.

The following step was to characterize the resistive behavior of the material and establish a maximum limitation value without destroying the material. In order to form a resistive curve, similar to ones referenced [4], elaborated based on the electrical value results. Following the specifications provided, it was assumed that the reduction of the first peak of current is due to the break of critical current density values, and the resistive evaluation derived from that point associated with the temperature rise. Comparing the fault current with the current limitation values obtained with the superconducting material several approximations to the resistive curves of the material were obtained by applying different currents, figure 1.1.

Analyzing those curves one comes to the conclusion that the initial resistance increases with the increase of the fault current and also temperature values, which consequently increases the resistance of the material in a proportionally.

These results don’t provide the necessary parameters to complete the system model and therefore understanding the thermal capacity of the material, although. Dimensioning the thermal capacity of the superconducting material is absolutely essential to determine the maximum limitation possible without destroying it.

IV. Three phase system

The second objective of this work is to implement a three phase assembly of the fault current limiter. The first idea is to repeat the mono-phase assembly three times, one for each phase. In an attempt to reduce the amount of superconducting material necessary for that assembly it is considered using a power rectifier with the material as charge. A bridge Rectifier converts a three phase alternate system into a mono-phase
continuous (DC) system. It applies on charge two segments of each voltage phase resulting in a signal with a frequency proportional to number of semi-conductors used. The main point of interest is the reflection of the charge on each phase in order to determine the current limitation. To do so, it’s assumed that all active power is transmitted to the rectifier charge and the expression is removed from the power balance (1.2) using the relation between input voltage and output voltage.

\[
P_{\text{transf}} = P_{\text{Rect}} \iff \\
\iff 3 \times \frac{V^2}{R} = \frac{3 \times 2 \times V^2}{R_0} \left( \frac{1}{2} + \frac{6}{4\pi} \sin \left( \frac{2\pi}{6} \right) \right) \iff \\
\iff \frac{R}{R_0} = 0.547
\]

Using this system brings several possible problems, such as voltage conduction that, in superconducting state, and compared with the voltage source may introduce significant values of power loss. To minimize this effect, instead of using diodes, alternative semi-conductors can be used, such as schottky diodes. These semi-conductors have a very low voltage drop, due to its metal-semiconductor barrier, and high current density. The only disadvantage is the leakage current that leads to thermal instability.

Alternative assemblies to the bridge can be used to minimize the voltage conduction factor such as:

- Half-bridge, which uses only three diodes but inserts a continuous (DC) component;
- Half-bridge with half-bridge in between that requires also six diodes and the use of three windings transformers.

Another possible disadvantage of using power rectifiers is the simultaneous conduction regime. The source inductance representing a line or a transformer limits the current growing rate that causes a delay in commuting between diodes. This delay implies simultaneous conduction of three diodes and consequently a two phase short-circuit (fig. 2.1) during this period. This results in an additional voltage drop on the charge, thus additional power loss. The German norms specify a value for the rectifier source inductance no greater than 5% of the voltage source inductance.

![Fig. 2.1 - Short-circuit representative scheme.](image)

In the study done so far it is assumed that the three phases are balanced, this is, they have the same amplitude and have a difference of 120º between phases. Since the network supply is never perfectly balanced it is necessary to use a tool that characterizes the resulting asymmetries. A variable transformation designated by
Fortescue matrix or symmetric component transformation transforms a three-phase system into three sets of independent equations called direct, inverse, and homopolar components. If the network is fully balanced, the transformation will only provide a direct component.

\[ C = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \quad a = e^{j\frac{2\pi}{3}} \]

(Eq. 1.3)

Using an assembly with the bridge rectifier, the system has an ideal response to the direct and homopolar components. So to check what happens to the real currents when an inverse component is inserted, various simulations were done, increasing the percentage of inverse component relative to the direct component \((Id, Ii = Id \delta e^{j\delta})\). The result showed that, when the inverse component has the same amplitude as the direct component, the three-phase system becomes a two-phase system where one phase has a difference of 180° to the other(s). The rectifier behaves like a mono-phase rectifier. The difference in phase angle between the direct and inverse component is responsible for the current distribution on each phase, for example, if the phase angle difference is π there will be one phase with no current, and the other two with the same current amplitude and phase angle difference of 180°.

To characterize the transformer in its symmetrical components, a global transformation matrix is used to convert the primary and secondary to direct, inverse and homopolar components. The type of construction and connections used determine the value of these components.

\[
\begin{bmatrix}
U_D \\
U_I \\
U_H
\end{bmatrix} = C^{-1}
\begin{bmatrix}
Z_f & 0 & 0 \\
0 & Z_f & 0 \\
0 & 0 & Z_f
\end{bmatrix}
\begin{bmatrix}
I_D^p \\
I_I^p \\
I_H^p
\end{bmatrix}
\]

\[
+ C_G^{-1} [Z_{trans}] C_G
\begin{bmatrix}
I_D^p \\
I_I^p \\
I_H^p
\end{bmatrix}
\]

\[
+ C^{-1}
\begin{bmatrix}
Z_c & 0 & 0 \\
0 & Z_c & 0 \\
0 & 0 & Z_c
\end{bmatrix}
\begin{bmatrix}
I_D^p \\
I_I^p \\
I_H^p
\end{bmatrix}
\]

\[
+ C^{-1} \delta n
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
I_D^p \\
I_I^p \\
I_H^p
\end{bmatrix}
\]

The objective is that the transformer has minimal dispersion and magnetization values \((C_G^{-1} [Z_{trans}] C_G = 0)\). Using three mono-phase transformers, the only connection that may affect the energy network is Wye – Wye without neutral, since in this type of solution, the homopolar current is forced into the magnetization winding that has a high homopolar impedance value, when compared to the three-leg transformer. Therefore this type of connection blocks the homopolar component from the network. It is possible to verify that if the defect has a
direct or inverse component and a homopolar component, the system on the secondary will be perfectly balanced. If the defect has both direct and inverse component and a homopolar component the system will detect it.

In case of small asymmetries there are no significant changes on the charge impedance reflex on each phase, this is, if one phase has a slight increase of resistance the other phases have a slight decrease.

Implementing the system in laboratory, it is necessary to consider the symmetrical components in order to preview the fault currents in the circuit. Mainly the fact that the rectifier does not respond to the homopolar component, and therefore the homopolar impedance of the limiting system is equal to the short-circuit impedance of the transformer. Proceeding with the experiment, the results showed in fact a current reduction in all fault cases. The result for the three-phase short-circuit is showed on figure 2.2 and 2.3, showing the current on the rectifier and on the affected phase on the network.

In table 1 is showed the results for the limitation on each fault case. As can be observed the major reductions are for the three-phase and phase-phase faults that are the ones where the homopolar component does not intervene. On the other two cases the reduction is minor because the superconducting material does not receive all the information regarding the fault current, since the homopolar is filtered by the rectifier.

Table 1 – System faults

<table>
<thead>
<tr>
<th></th>
<th>(I_{cc}) [A]</th>
<th>(I_{limited}) [A]</th>
<th>Reduction [%]</th>
<th>(I_{regime}) [A]</th>
<th>Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-Phase</td>
<td>6,08</td>
<td>4,65</td>
<td>-23,52</td>
<td>3,68</td>
<td>-20,86</td>
</tr>
<tr>
<td>Phase-Earth</td>
<td>6,68</td>
<td>5,92</td>
<td>-11,38</td>
<td>5,68</td>
<td>-4,05</td>
</tr>
<tr>
<td>Phase-Phase</td>
<td>4,92</td>
<td>3,88</td>
<td>-21,14</td>
<td>3,52</td>
<td>-9,28</td>
</tr>
<tr>
<td>Phase-Phase-Earth</td>
<td>6,52</td>
<td>5,30</td>
<td>-18,71</td>
<td>4,88</td>
<td>-7,92</td>
</tr>
</tbody>
</table>
The second reduction column is related to the increase of resistance due to thermal effect. Here one comes to same conclusion, when the superconducting material receives all information the thermal effect is more noticed.

V. Conclusion

In conclusion it was verified that the three-phase and phase-phase fault where limited within the same values obtained in the mono phase limitation system. The weak point of this system is the phase-phase-earth and mainly the phase to earth fault, which may be the most harmful defect, depending on the symmetrical components, and the least limited by the fault current system.

VI. References


