Status and outlook on superconducting fault current limiter development in Europe

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Abstract: The application of superconducting fault current limiters (SCFCLs) in power systems is very attractive because SCFCLs offer superior technical performance in comparison to conventional devices to limit fault currents. Negligible impedance at normal conditions, fast and effective current limitation within the first current rise and repetitive operation with fast and automatic recovery are the main attributes for SCFCLs. In recent years there has been worldwide a significant progress in R&D of SCFCLs. Especially in Europe several projects demonstrated the feasibility of SCFCLs in medium voltage applications. This paper gives an extended review of the present state-of-the-art of SCFCL development, with favourable applications from a European point of view. It is further discussed which SCFCL concepts and materials seem most promising for future applications. It can be summarized that SCFCLs are, at present, not commercially available but several successful field tests demonstrated the technical feasibility of SCFCLs at the medium voltage level. The development of a transmission type SCFCLs has been started in Germany and the US and first successful intermediate tests are expected soon. In general, considerable economical and technical benefits can be achieved by applying SCFCLs at the distribution and transmission voltage level.

Keywords: Fault Current Limiters, Short-circuit

1. INTRODUCTION

The short-circuit current level in electric power systems will increase in future due to increased de-centralized generation and more urban power systems with high power density. One favorable device to limit short-circuit currents without increasing the power system impedance at normal operation is the superconducting fault current limiter (SCFCL). Due to its fast and effective short-circuit current limitation within the first current rise, the automatic recovery and the fail safe operation, the application of SCFCLs is very attractive. The general operation modes and some important parameters of SCFCLs are shown in Fig. 1. During normal operation the SCFCL impedance is negligible and the SCFCL is designed to carry the rated current \(i_r\). Without SCFCL the short-circuit current would rise up to the peak value \(i_p\), but due to the fast limitation the current is limited to a maximum current \(i_{\text{max}}\) within the first current rise.

After the clearing of the short-circuit usually, a short recovery time \(t_r\) is needed to re-cool the SCFCL to its original temperature. The recovery time depends on the SCFCL type and the design and ranges from zero up to less than a minute. An important parameter for SCFCLs is the so-called limitation factor, the ratio of the maximum limited current \(i_{\text{max}}\) divided by the peak value of the rated current \(i_r\).

This paper shortly describes the most attractive SCFCL concepts, presents favorable SCFCL applications from a European point of view and shows the state-of-the-art of SCFCL development. Due to the fast progress with SCFCL projects using YBCO coated conductors a comparison of the quench behavior of different YBCO coated conductors is added.

2. FAVORABLE SCFCL CONCEPTS

In general, many different SCFCL concepts are known. The most popular ones are the resistive type SCFCL, the bridge type SCFCL, the DC biased iron core type SCFCL and the shielded core type SCFCL. A comprehensive summary on different SCFCL concepts is given in [1].

At present, the author knows no new active project to further develop a shielded core type SCFCL. Therefore, this paper shortly describes the function of resistive type SCFCLs, bridge type SCFCLs and DC biased iron core type SCFCLs.

2.1. Resistive SCFCL

The electrical circuit of a resistive type SCFCL is shown in Fig. 2. During normal operation the superconducting material is in the superconducting state and the resistance \(R_{sc}\) is zero. At the short-circuit the current rises above the critical current \(I_c\) of the superconductor and...
Thus a resistance $R_{SC}$ develops rapidly. This resistance heats the superconductor usually above its critical temperature $T_c$ and this means that after the short-circuit time $t_d$ (equal to fault clearing time) a recovery time is needed to re-cool the superconductor to its operation temperature. A resistance in parallel $R_{SH}$ is needed to avoid hot spots during quench, to adjust the limiting current and to avoid overvoltages due to the fast current limitation. In comparison to other SCFCL types the resistive type SCFCL is the most compact type and offers full recovery within a few seconds. The major characteristic of a resistive SCFCL are:

+ compact
+ low weight
+ fail safe
- current leads to low temperatures

### 2.2. DC biased iron core SCFCL

It is well known that the non-linear characteristic of iron cores can be used for current limiting device. The basic electric scheme of a DC biased iron core SCFCL is shown in Fig. 3. At normal operation currents both iron cores are driven into saturation with direct currents $i_{DC1}$ and $i_{DC2}$. As a result the impedance is low, consisting mainly of the two air coil impedances $L_1$ and $L_2$ and their resistances. In the case of a fault, the large AC current $i_{AC}$ will alternately drive the two coils out of saturation and into the region of high permeability on the magnetization curve resulting in a significant increase of the apparent coil inductance. The superconductor is used only for the DC windings, which means that this type of SCFCL needs the smallest amount of superconductor and that no superconductor AC losses have to be considered. The major characteristic of a DC biased iron core type SCFCL are:

- no superconductor quench, immediate recovery
- superconductor for DC only
- adjustable trigger current
- high volume and weight
- high impedance during normal operation

### 2.3. Bridge type SCFCL

The basic electrical circuit of this bridge type SCFCL is shown in Fig. 4. A full rectifier bridge, a limiting coil and a voltage source is needed for this type of SCFCL. At normal operation the amplitude of $i_{AC}$ is lower than the DC current $I_0$ and therefore all diodes are conducting. The limiting coil $L$ sees the DC current only. If $i_{AC}$ gets higher than $I_0$ then the diodes $D_3$ and $D_4$ will arrest at the positive half cycle and thus the current is limited by the inductance $L$. At the negative half cycle the diodes $D_1$ and $D_2$ will arrest if $i_{AC}$ is larger than $I_0$. Thyristors instead of diodes enable a fast turn-off of the current within a half cycle. The major characteristic of a bridge type SCFCL are:

- no superconductor quench (L can be non-SC)
- immediate recovery
- adjustable trigger current (depends on $I_0$)
- not fail safe
- losses in semiconductors

### 3. SCFCL APPLICATIONS

It is obvious that there are many potential applications in power systems for SCFCLs. An extended overview about the different applications is given in [1]. The applications can be divided into applications at distribution and transmission voltage level and the technical and economical benefits depend very much on the specific application and the specific situation in the power system. This has been described earlier in [2].

Favorable SCFCL applications at distribution voltage level are:

- SCFCL in busbar coupling
- SCFCL in transformer feeder
- Coupling of dispersed generation with SCFCLs
SCFCL is technically feasible. The high temperature superconductor material was reported [7]. In Korea a successful high power laboratory short-circuit test with a single phase 13.2 kV, 630 A SCFCL demonstrator was performed in 2007. In March 2007 another successful test with a single phase 7.5 kV, 267 A SCFCL demonstrator was reported in Germany.

It can be summarized that medium voltage SCFCLs of each type are technically feasible and that it is very likely to see soon first pre-commercial SCFCL application for this voltage level. Further R&D effort should concentrate on reducing cost and demonstrating long term stability and reliability.

4.2. Transmission level SCFCLs

A major reason to develop SCFCLs for the transmission voltage level is that there exists no conventional device with an active current limitation and low impedance during normal conditions. In addition, studies showed that high savings and many benefits can be achieved at this voltage level.

The first project to develop a HTS transmission type SCFCL started in 2003 in the US [8]. During the project it turned out that the concept of a so-called matrix type fault current limiter (MFCL) is difficult to adapt to high voltage levels. As a result this project was discontinued for some time. In 2006, new partners joined this project and the concept was changed to a resistive SCFCL with YBCO coated conductors. A successful intermediate test was reported in [9] and the main objective is to develop a 138 kV, three phase resistive SCFCL until 2009.

In 2005 a project in Germany started to develop a 110 kV, 1.8 kA single phase resistive SCFCL until 2008. This project uses MCP-BSCCO 2212 tubes with a magnetic field assisted quench concept [10]. The status and the concept are reported in [11]. A major challenge in this project is to develop the HTS component for all relevant short-circuit levels.

In June 2007 the US Department of Energy announced two new transmission level SCFCL projects [12]. A 115 kV three phase resistive type SCFCL and a 138 kV three phase DC biased iron core type SCFCL will be developed.
Within the last phase of the Korean DAPAS program it is foreseen to develop a 154 kV SCFCL until 2010. It is not yet decided which type of SCFCL will be taken. Intermediate successful tests with 22.9 kV demonstrators were performed with a hybrid type and a resistive type SCFCL. A major challenge for transmission level SCFCLs will be to demonstrate a reliable high voltage insulation concept for AC voltages and lightning impulses.

5. QUENCH BEHAVIOUR OF YBCO COATED CONDUCTORS

The recent progress in R&D of YBCO coated conductors (CC) make them attractive candidates for resistive SCFCLs. Therefore, a comparison of industrial available coated conductors has been performed. Coated conductors are able to handle currents over $I_c$, the so called quench for some net cycles. The behavior at these over currents depends strongly on the homogeneity of the critical current along the coated conductor, its stabilization and the amplitude of the over current as well.

### 5.1. Samples and test circuit

Low stabilized CC with a silver cap-layer only and high stabilised CC with silver layer and additional copper or stainless steel coating were tested. Table 2 lists the specifications of the test samples. All samples were 11cm long and the voltage along the conductor was measured each single centimeter. A transformer supplied the 50 Hz sinusoidal current. The peak value of the prospective current ($i_p$) was adjusted with an infinitely variable resistance in serial to the test samples. Therefore, low short circuit currents (<3 times $I_c$) as well as high short circuit currents with more than 10 times $I_c$ can be adjusted. For the comparison of the CC with their different critical currents $i_p$ was normalized with $I_c$.

### 5.2. Quench behaviour at low short-circuit currents

The high stabilised coated conductors are unable to limit the short circuit current noticeable due to their low resistance (see Fig. 6). There is no significant increasing of the resistance of the high stabilised CC even after 4 net cycles.

The low stabilised coated conductors limit the short circuit current on the other hand already at low short circuit currents evidently with a limitation factor ($f_{lim}$) around 1.2.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Stabilisation</th>
<th>Homogeneity</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silver (rd. 2.5µm)</td>
<td>1%</td>
<td>rd. 12</td>
</tr>
<tr>
<td>2</td>
<td>Silver and copper</td>
<td>5%</td>
<td>rd. 4</td>
</tr>
<tr>
<td>3</td>
<td>Silver and stainless steel</td>
<td>&gt;14%</td>
<td>rd. 4</td>
</tr>
<tr>
<td>4</td>
<td>Silver (rd. 0.5µm)</td>
<td>&gt;9%</td>
<td>rd. 10</td>
</tr>
<tr>
<td>5</td>
<td>Silver (rd. 5µm)</td>
<td>&gt;10%</td>
<td>rd. 10</td>
</tr>
</tbody>
</table>

This short circuit level is the major challenge for inhomogeneous coated conductors. The slow increasing current in the beginning of low short circuit causes unbalanced resistance along the conductor with a low stabilisation. Fig. 7 shows the voltage and the resistance distribution respectively of a low stabilised and inhomogeneous coated conductor at low short circuit currents. Sections with higher critical currents may not able to build up a sufficient resistance to protect sections with lower critical currents of overheating. Therefore, the voltage drops only on a few sections. This may causes a damage of the coated conductor.

With a higher stabilization, the unbalances of the resistivity gets efficiently smoothed. Fig. 8 shows the more balanced voltage distribution on an inhomogeneous but high stabilised coated conductor.
5.3. Quench behaviour at high short-circuit currents

All of the tested samples show a limitation of the current at high short circuit currents (see Fig. 9). Even the very high copper stabilised one shows a more or less noticeable limitation. The low stabilised coated conductors reach limitation factors around 4 at this level.

The inhomogeneous coated conductors show an uncritically distribution of the resistance at this short circuit level. Even sections with lower critical currents build up a sufficient resistance to protect sections with higher critical currents.

5.4. Summary of quench behaviour

All of the tested coated conductors showed the expected quench behaviour in respect to their stabilisation and critical current homogeneity. Very high stabilised coated conductors can hardly limit the current at all short circuit current levels. On the other hand high stabilised coated conductors are able to limit the short circuit current at the high level. The low stabilised coated conductors reach the highest limitation factors at all and limit the current at every short circuit current level.

The following statements summarize the results of the made study:

- Inhomogeneous coated conductors with low stabilisations are hardly able to withstand low short circuit currents. They need a higher stabilisation for the protection of hot spots.
- With the increasing of short circuit current amplitudes the importance of the critical current homogeneity diminishes.
- A good stabilisation can smooth the inhomogeneity of the coated conductor even at low short circuit currents to the disadvantage of limitation ability.
- Homogeneous coated conductors are able to limit a wide range of short circuit current amplitudes without the risk of damage.

6. SUMMARY AND OUTLOOK

SCFCLs are new and attractive devices in power systems to limit short-circuit currents in power systems. At present SCFCLs are not commercially available but many projects underlined their feasibility in medium voltage level applications. In addition, several projects are on their way to develop SCFCLs for the transmission voltage level. Most present projects follow the resistive type SCFCL, very likely because of the simple concept and the low volume and weight. In Europe, the most favourable SCFCL applications are those with high savings. This is especially the case in power system auxiliaries and in the coupling location of 110 kV subgrids. The investigation of YBCO coated conductors shows that low level short-circuits has to be taken into account for the tests of SCFCLs and that a good stabilization of the conductor is more important for quench stability than the $I_c$ homogeneity.

REFERENCES

3. Pfeiffer K, Schwarz H 2006 Applications of resistive high
Table 1. Important FCL projects (Status July 2007)

<table>
<thead>
<tr>
<th>Lead Company</th>
<th>Country / Year</th>
<th>Type</th>
<th>Data</th>
<th>Phase</th>
<th>Superconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCEL/Nexans SC</td>
<td>Germany / 2004</td>
<td>Resistive</td>
<td>6.9 kV, 600 A</td>
<td>3-ph.</td>
<td>BSCCO 2212 bulk</td>
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<td>Nexans</td>
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<td>Resistive-inductive</td>
<td>63.5 kV, 1.8 kA</td>
<td>1-ph.</td>
<td>BSCCO 2212 bulk</td>
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<td>KEPRI</td>
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<td>Resistive</td>
<td>13.2 kV, 630 A</td>
<td>3-ph.</td>
<td>BSCCO 2212 bulk</td>
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<tr>
<td>General Atomics</td>
<td>US / 2002</td>
<td>Diode bridge</td>
<td>7.2 kV, 1.2 kA</td>
<td>3-ph.</td>
<td>BSCCO 2223 tape</td>
</tr>
<tr>
<td>Yonsei University</td>
<td>Korea / 2004</td>
<td>Diode bridge</td>
<td>3.8 kV, 200 A</td>
<td>3-ph.</td>
<td>BSCCO 2223 tape</td>
</tr>
<tr>
<td>CAS</td>
<td>China / 2005</td>
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<td>6 kV, 1.5 kA</td>
<td>3-ph.</td>
<td>BSCCO 2223 tape</td>
</tr>
<tr>
<td>Innopower</td>
<td>China / 2007</td>
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<td>20 kV, 1.6 kA</td>
<td>3-ph.</td>
<td>BSCCO 2223 tape</td>
</tr>
<tr>
<td>Zenergy power</td>
<td>Aus,US,D / 2009</td>
<td>DC biased iron core</td>
<td>-</td>
<td>3-ph.</td>
<td>BSCCO 2223 tape</td>
</tr>
<tr>
<td>KEPRI</td>
<td>Korea / 2004</td>
<td>Resistive</td>
<td>3.8 kV, 200 A</td>
<td>3-ph.</td>
<td>YBCO thin films</td>
</tr>
<tr>
<td>CRIEPI</td>
<td>Japan / 2004</td>
<td>Resistive</td>
<td>1 kV, 40 A</td>
<td>1-ph.</td>
<td>YBCO thin films</td>
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<tr>
<td>Mitsubishi</td>
<td>Japan / 2004</td>
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<td>200 V, 1 kA</td>
<td>1-ph.</td>
<td>YBCO thin films</td>
</tr>
<tr>
<td>AMSC / Siemens</td>
<td>US / Germany /</td>
<td>Resistive</td>
<td>66 kV, -</td>
<td>3-ph.</td>
<td>YBCO coated cond.</td>
</tr>
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<td>IGC Superpower</td>
<td>US / 2009</td>
<td>Resistive</td>
<td>80 kV, -</td>
<td>3-ph.</td>
<td>YBCO coated cond.</td>
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<td>Rolls Royce</td>
<td>UK / -</td>
<td>Resistive</td>
<td>6.6 kV, 400 A</td>
<td>-</td>
<td>MgB_2</td>
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<td>EPRI / Powell</td>
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<td>Power electronics</td>
<td>8 kV, 1.2 kA</td>
<td>3-ph.</td>
<td>Without SC</td>
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<td>Siemens</td>
<td>Germany / 2004</td>
<td>Power electronics</td>
<td>6.9 kV, 25 MVA</td>
<td>3-ph.</td>
<td>Without SC</td>
</tr>
</tbody>
</table>

1) year of test  
2) phase to ground voltage