SUPERCONDUCTING FAULT CURRENT LIMITERS - GETTING A GRIP TO SHORT CIRCUIT CURRENTS

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INTRODUCTION

Among the innovative ideas that high temperature superconductivity (HTSC) has brought about are superconducting fault current limiters. These items of equipment limit the short-circuit current by changing from the superconducting state to the normal-conducting state well before the first peak value of the short-circuit current is reached. Basically there are two technical options for a superconducting fault current limiter concept, the resistive and the inductive fault current limiter. The paper compares both options and describes the electrical behavior and preferred locations for an application of superconducting fault current limiters.

RESISTIVE AND INDUCTIVE ALTERNATIVES

Superconducting **f**ault **c**urrent **l**imiters (SFCL) are a promising application of superconductors in power distribution networks. Ideally they combine features, which in sum cannot be provided by conventional devices:

- ⇨ Negligible influence during normal operation
- ⇨ Effective reduction of short circuit currents (well before the first current peak)
- ⇨ Intrinsic safety
- ⇨ Self-restoring capability.

Several types of SCFL concepts have been proposed so far, an overview is given in [1].
Basically there are two technical options to choose from:

- ⇨ the resistive limiter and
- ⇨ the inductive limiter.

Some hybrid-type limiter concepts have been developed too, but will not be considered here [2].
In the case of resistive type, the limiter is connected directly into the short-circuit current path and the normal load currents as well as short-circuit currents flow through the superconductor. Figure 1 shows a simplified electrical arrangement and Figure 2 a principal schematic view of a resistive superconducting fault current limiter. Should the current exceed a certain limit the superconductor loses its superconducting ability very fast and becomes normal conducting (‘quenches’). The corresponding increase in resistance effectively limits the fault current.

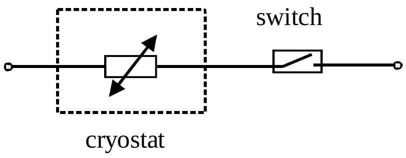

Figure 1: Simplified electrical equivalent of a resistive SFCL.

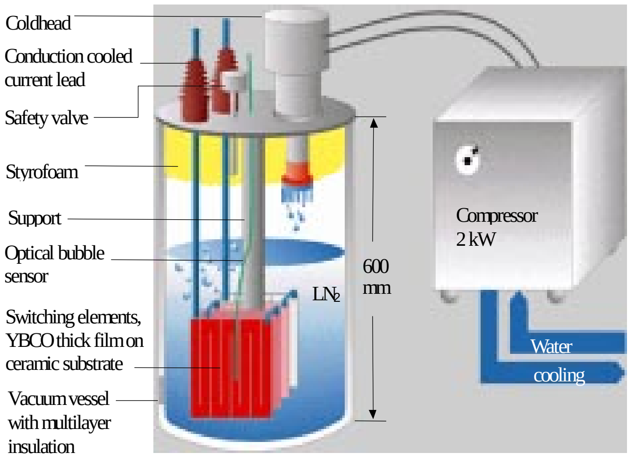

Figure 2: Principle schematic view of a resistive SFCL.

Once the superconductor has gone normal conducting it heats up very fast due to Joule dissipation. To avoid overheating a mechanical switch opens the circuit within a few half cycles after occurrence of the fault. The limiting elements then automatically cool back to their normal operating temperature and the superconducting state is regained. Thus the circuit might be closed again for continued operation. For resistive type limiters the recovery time is of the order 1 - 2s.
Some model-type resistive limiters have been developed so far. Siemens demonstrated a liquid nitrogen cooled 100kVA-limiter made of thin films of high temperature superconducting material [3]. An 1 MVA unit has been already built and is being tested at the moment.
In principle the inductive current limiter is a kind of transformer in which the superconducting material screens the magnetic field of the primary copper winding from the iron core during normal operation [4].
Therefore it is often called a ‘shielded iron core’-type limiter in the literature. Contrary to the resistive limiter the superconductor is only magnetically coupled into the current path.

Figure 3 shows the simplified electrical equivalent and Figure 4 the principle arrangement of an inductive superconducting fault current limiter.
The primary coil of the limiter is normal conducting and consists of several windings analogous a conventional coil. The secondary side is superconducting and consists in most approaches just of one single superconducting winding, which is a tube.

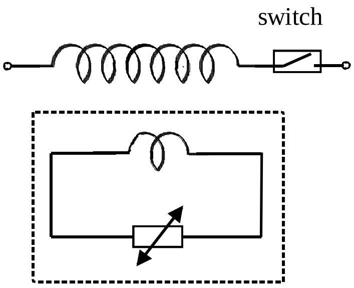

Figure 3: Simplified electrical equivalent of an inductive SFCL.

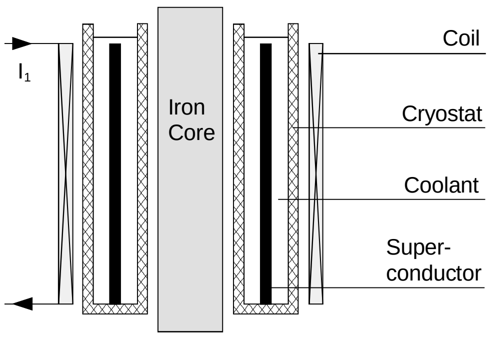

Figure 4: Schematic cross section of an inductive SFCL.

During normal operation the magnetic field of the primary coil is screened by the superconductor completely and does not enter the iron core. If the current rises above a certain level the critical magnetic field of the superconductor is exceeded and the field penetrates the iron core. The resulting (increased) impedance of the device then limits the short circuit current.
Like the resistive type the inductive current limiter needs a current interruption following a limiting action and a recovery period too.

RESISTIVE OPERATING CHARACTERISTICS

The operating characteristics of a resistive type limiter is to be considered in the following in some more detail. Figure 5 shows a measurement done during the action of a 100 kVA model current limiter which was developed and built at Siemens R&D laboratories [3]. At time $t = 0$ a short circuit is made deliberately and the current rises quickly according to the short circuit impedance. Exceeding the critical current I_c the superconductor becomes normal conducting (quenches) and develops considerable resistance in less than 1 ms. After the quench virtually the whole source voltage falls off at the limiter (dashed line in Figure 5). The current is thereby effectively reduced to even below the rated current level and is finally switched off after 45 ms.

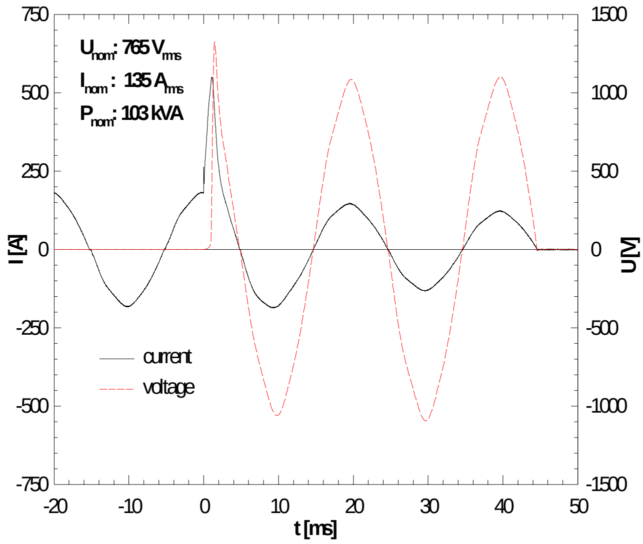

Figure 5: Current and voltage as function of time during a 100kVA limiting experiment [3].

The performance of a resistive type current limiter strongly depends on the type of superconductor or material used therein. In Figure 6 the limiting behavior of three different samples is compared by relating the absolute current to the critical current of the superconductor. Sample A consists of a YBaCuO thin-film, thermally evaporated on a polycrystalline YSZ substrate with a critical current density j_c of $2.4 \cdot 10^4$ A/cm^2.
For sample B j_c is twenty times higher ($5.0 \cdot 10^5$ A/cm^2) due to a special buffering technique before YBaCuO-deposition, whereas sample C (YBaCuO thin-film on single crystalline sapphire substrate) shows the highest $j_c = 2.5 \cdot 10^6$ A/cm^2.
Figure 6 shows the different behavior of the first current peak in detail. The peak-let-through currents of samples A, B and C are 7.5, 4.8 and 3.0 times the critical current respectively. It can be concluded that there is a definite relationship between critical current density and peak-let-through current.
Fig. 7 shows the limitation of the current after the quench until the disconnection. In the fifth half cycle after fault occurrence the current is limited by sample A and B not below two times the rated current I_r (usually I_r is fixed at $I_r = I_c/1.41$).
In contrast sample C limits the fault current even below the rated current. By chance sample A and B limit the fault current to nearly the same level despite of the different j_c. This might be explained by a thin layer of gold which is deposited on top of the YBaCuO-layer of sample B and which acts as a shunt thereby reducing the normal state resistance of the YBaCuO.

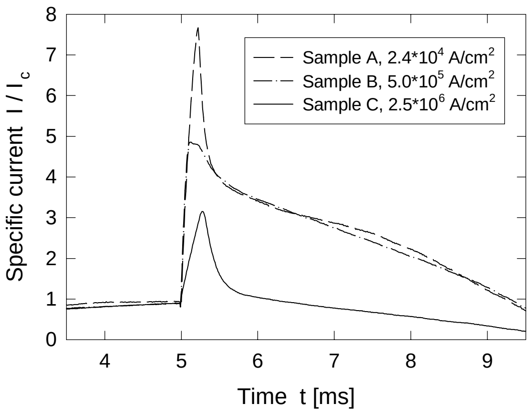

Figure 6: Limiting behavior of different samples at the first current peak.

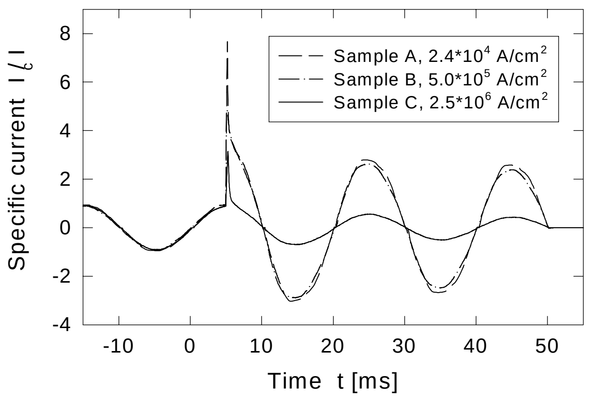

Figure 7: Limiting behavior of different samples related to current density.

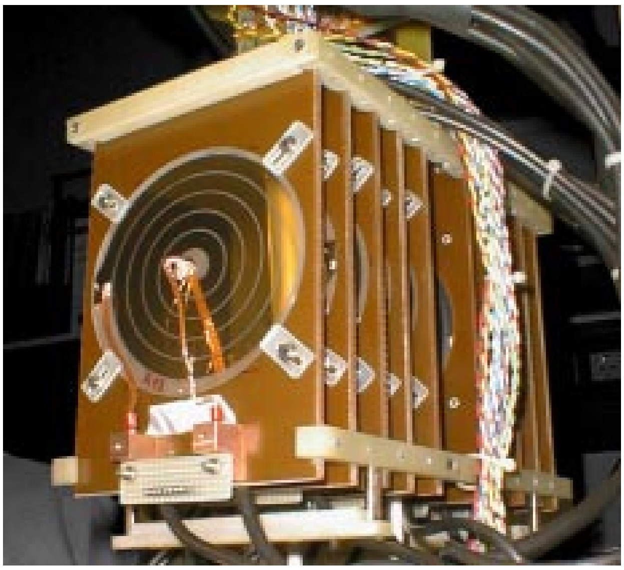

Figure 8: Switching elements of the 100kVA resistive SFCL.

COMPARISON RESISTIVE AND INDUCTIVE

Siemens has developed and built a 100 kVA functional model of a resistive SFCL [3]. Ten switching elements are assembled to achieve the overall nominal switching power of P_{nom} = 100 kVA. Each of them consists of a YBaCuO film with a thickness of 250 nm deposited on 4 " sapphire wafers. A spiral shape with a length of 80 mm and a path width of 7 mm was etched into the layer structure.
Figure 8 shows the positioning of the ten switching elements. The spacing between the elements is 2 cm and the overall dimensions of the ten elements are 22 cm x 15 cm x 12 cm.

Some characteristics of the resistive 100kVA-model are summarized in the following table:

Rated power	100 kVA
Number of phases	Single-phase
Rated voltage	765 V
Rated current I_r	135 A_{rms}
Prospective short circuit current	$15*I_r$
Peak-let-through current	$3*I_r$
Current interruption after	50 ms
'Steady' limiting current	$0.9*I_r$
Recovery time	1 - 2 s
Specific volume (estimated, without liquid nitrogen supply)	< 1 m^3/MVA
Specific weight (without cryostat)	< 0.2 kg/kVA

In a joint project together with the Canadian power utility Hydro Quebec, Siemens and Hydro Quebec have studied the practical feasibility of both types of high temperature super- conducting fault current limiters. A comparison of costs and operating characteristics and the possibility of upscaling the equipment to ratings to be used in distribution networks showed clear advantages for the resistive type. Figure 9 compares the technical and economic data for resistive and inductive limiters.

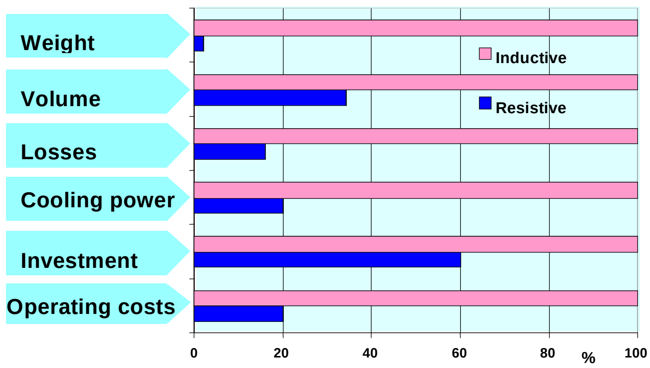

Figure 9: Comparison of resistive and inductive limiters.

REQUIREMENTS

To be in position to meet the requirements for application in an electrical power system, the SFCL must posses the following characteristics [5]:

- ⇨ The SFCL must be intrinsically safe.
- ⇨ When a short circuit occurs, the SFCL must quench well before the first peak value is reached and limit the fault current.
- ⇨ Transient phenomena, which arise when compensating circuits and transformers are energized or motors start up, must not cause the limiter to quench.
- ⇨ The overvoltage that occurs during quenching must be within levels that are below the permissible dielectric strength for the equipment of the voltage level in question.
- ⇨ The selectivity of protection equipment must not be affected.
- ⇨ The recovery period, and therefore the time until reclosure must be as short as possible.
- ⇨ The SFCL must be able to be integrated into existing installations.
- ⇨ The service life of the SFCL must be comparable with that of conventional equipment.

APPLICATIONS

High short-circuit rating has many advantages despite the fact, that it is not entirely unproblematic due to the high stress levels that it involves and the demands that it makes to the switchgear. As system short-circuit levels rises, voltage dips and fluctuations caused by very large or fluctuating loads become fewer. This means that voltage quality for the many customer loads that are sensitive to fluctuations in voltage is improved and flicker and distortion due to sources of harmonics are reduced. However, the indirect effect which causes short-circuit currents to be exerted on instrumentation, control and remote signaling circuits is increased. Similarly, the elevated potentials which can lead to dangerous step voltages and touch voltages are also higher. The high short-circuit currents impose very much higher stress loads on plant and equipment and necessitate the replacement of equipment even when the value is exceeded. In the past when power systems have reached the limit of their short-circuit withstand capability, there have been three options for adapting them to the higher stress levels involved:

- ⇨ separation, i.e. the use of extra feeder transformers,
- ⇨ current-limiting reactors or
- ⇨ transition to higher voltage level.

Now, however, a further option will be the linking-together of individual power systems, with superconducting fault current limiters. Thanks to the reversible mode of operation it will be possible to reconnect the power systems within 1-2 seconds of a fault being cleared.

The primary purpose of a SFCL is to control the short circuit capacity of a substation from exceeding the momentary and interrupting capacity of downstream devices as system short circuit capacity is increased. The location and rating of a SFCL will be dependent on the distribution substation configuration and current capacity of the incoming transformer feeders and loads in the outgoing feeders.
Figure 10 shows fault locations and possible installation locations of current limiting devices in a medium voltage system. According to this figure potential installation locations of SFCLs will be conceivable in:

- ⇨ outgoing feeders
- ⇨ tie feeders or
- ⇨ incoming feeders.

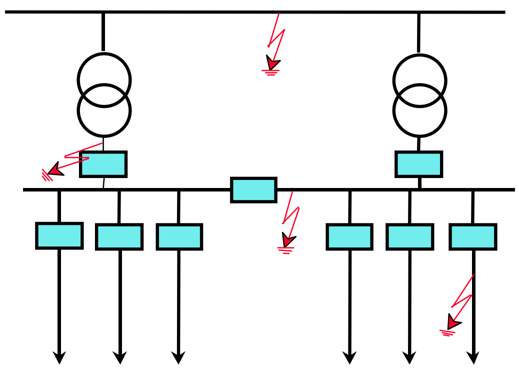

Figure 10: Fault locations and possible installation locations of current limiting devices.

ADVANTAGES

The recipe for success in the rapid development of the resistive fault current limiter has been the manufacture of a suitable superconducting material that is deposited in a very thin layer on ceramic plates. Beside the process of manufacture questions about potential applications and economic aspects have to be considered too.
In the early days, of course, a superconducting fault current limiter is very unlikely to be cheaper than a conventional circuit-breaker. The higher costs for a current limiter will however be compensated by its advantages in the power system:

- ⇨ Lower thermal, mechanical and electrodynamical stressing of equipment and systems.
- ⇨ Enhanced supply reliability by means of coupled busbars.

- ⇨ Enhanced flexibility in operation and design of networks.
- ⇨ Improved capacity utilization with the use of several injection transformers.
- ⇨ Less need for spares.
- ⇨ No increase in short-circuit rating and therefore no need or postponement of investment in new equipment.
- ⇨ Accommodate growth or independent power producers hook-up without having to upgrade existing installations.
- ⇨ High energy supply quality yet low fault currents.

Superconducting fault current limiters are especially necessary when other superconducting equipment such as transformers, cables or energy storage is being used a an electrical system in the future. With their short response times the limiters protect the equipment while also preventing quenching in the equipment itself which, due to the long cooling times involved, could lead to undesirable outages. At about 1-2 seconds, the re-cooling time of the superconducting fault current limiter is markedly less than that of the other superconducting equipment.

The use of superconducting fault current limiters brings benefits:

- ⇨ when systems are growing rapidly,
- ⇨ when they are deeply meshed,
- ⇨ when new power stations are to be added,
- ⇨ when there are high concentrations of load, e.g. in city centres and industrial power supply systems.

SUMMARY

The use of superconducting fault current limiters in electrical power systems opens up what at first sight appears to be a contradictory possibility to operate systems with low system impedance and low fault current levels.

Lower system impedance and consequently favorable behavior with respect to network perturbation can be achieved by means of a greater degree of system meshing.

SFCLs are in the position to divide network subsystems in less than 1 ms, that is, even before the first peak value of the fault current is reached.

The development of SFCLs is already in an early stage and therefore, of course, a superconducting fault current limiter is very unlikely to be cheaper than a conventional circuit-breaker. But, the advantage gained by system operators from using these new devices will be of crucial importance for the further development and more widespread use of SFLC technology in electrical power systems.

A comparison of the characteristics of an inductive and a resistive SFCL shows advantages in volume, weight and losses for the resistive concept.

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