FCL : A solution to fault current problems in DC networks

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Abstract. Within the context of the electric power market liberalization, DC networks have many interests compared to AC ones. New energy landscapes open the way of a diversified production. Innovative interconnection diagrams, in particular using DC buses, are under development. In this case it is not possible to defer the fault current interruption in the AC side. DC fault current cutting remains a difficult problem. FCLs (Fault Current Limiters) enable to limit the current to a preset value, lower than the theoretical short-circuit current. For this application Coated Conductors (CC) offer an excellent opportunity. Due to these promising characteristics we build a test bench and work on the implementation of these materials. The test bench is composed by 10 power amplifiers, to reach 4 kVA in many configurations of current and voltage. We carried out limiting experiments on DyBaCuO CC from EHTS, samples are about five centimeters long and many potential measuring points are pasted on the shunt to estimate the quench homogeneity. Thermal phenomena in FCLs are essential, numerical models are important to calculate the maximum temperatures. To validate these models we measure the CC temperature by depositing thermal sensors (Cu resistance) above the shunt layer and the substrate. An electrical insulation with a low thermal resistivity between the CC and the sensors is necessary. We use a thin layer of Parylene because of its good mechanical and electrical insulation properties at low temperature. The better quench behaviour of CC for temperatures close to the critical temperature has been confirmed. The measurements are in good agreement with simulations, this validates the thermal models.

1. Introduction

The natural and instantaneous electric field development by a superconductor above its critical current opens a very interesting and innovating solution for the fault current limitation. The developed field balances the grid voltage and limits the current to a defined value, easy to interrupt by a switch. Superconducting Fault Current Limiters (SCFCL) solve the fault current problem and reduce the line apparatus stresses due to the current excursion beyond the rated value. Also, in DC networks rated operation, superconductors do not create losses and only a low power with moderate cost cooling system is required. This is important because the cryogenic cost remains one of the main drawbacks for the superconducting industrial applications. So SCFCL will largely contribute to DC network development.
2. The resistive SCFCL

2.1. Introduction

The current limitation uses the variable impedance principle which could be resistive in DC networks. The current is limited by a very fast impedance increase (< 1 ms), able to limit the first current peak at a threshold value, lower than the theoretical short-circuit value. During the short-circuit, the limiting device is practically supplied by the network voltage and the dissipated power is very important. HTS (High Temperature Superconductor) are very interesting for current limitation, because of their zero resistivity in the superconductive state and their strong resistivity in the normal state. Repetitive and natural operation also confers considerable assets to SCFCL. However, as any superconductive system it requires a cryogenic environment made of a cryostat and a cryogenic fluid or a cryo-cooler.

2.2. Theoretical model

2.2.1. Superconductor state

In this state, the SCFCL is in its rated operating mode. The total current flows through the HTS because its zero resistivity shorts-circuit the shunt and the substrate (Fig 1). This state is defined by two limits: Tc an Jc which depends on the operating temperature.

![Fig 1: The resistive SCFCL in its superconducting state](image)

2.2.2. Quench

When a short-circuit appears on the network, the current grows very quickly and exceeds the HTS critical current, which starts to quench. An electric field appears along the CC and a current starts to circulate in the shunt and the substrate. The equivalent CC diagram is the three parallel layers (Fig 2). This state is very important for the current limitation because an inhomogeneous quench can burn the HTS. A superconductor generally does not quench in a homogeneous way, but on one or more discrete areas which propagate with the current limitation, until reaching the total length of the CC. In order to avoid localised temperature rises called “hot spots”, it is necessary to homogenize the quenches. The University of Geneva proposed to use HTS geometry with constrictions, to create a homogeneous quench area along the HTS [1]. Within the framework of our study we choose another solution consisting in working near to the critical temperature of the HTS [2].
2.2.3. Current limitation

A resistive SCFCL in its limitation state [3] looks like a resistor placed in serie with the network. In this state the superconductor is supposed to have entirely quenched, energy is dissipated in a homogeneous way along the CC. Dissipated energy can reach important values so it is necessary to control the temperature rise with the CC geometry and its cooling. During the current limitation the SCFCL has accumulate thermal energy, which is necessary to dissipate. After the short circuit opening by a switch, the limiting device enters a recovery phase and releases the thermal energy stored until reaching its assigned temperature.

2.3. Current limiting tests

2.3.1. Introduction on coated conductor

HTS based on coated conductors (CC) target high current transport and also high magnetic field production due to the use of YBCO. Many efforts have been made on CC developments to reach impressive results. Currently more than 15 MA/cm² at 77 K / 0 T in Ion Beam Assisted Deposition (IBAD) oxide on polycrystalline stainless steel (SS) and long length samples are produced using physical methods (PLD) [4][5].

2.3.2. Sample and test bench

A two meter long coated conductor from EHTS [6] was investigated in a fault current limiter configuration. The CC was composed of a SS substrate (100 µm) covered with 1.9 µm thick layer of YBCO with a shunt made of gold layer 0.25µm thick. The conductor had a critical current of 47.5 A at 77 K / 0 T. The coated was installed on a glass fiber cylinder equipped with several voltage measurement taps to characterize different parts along the conductor during the limiting tests (Fig 3). The current limitation tests consist in applying a continuous voltage during a few milliseconds in order to simulate a short-circuit. A power amplifier bench is used as a voltage supply controlled by computer. In order to operate at various temperatures, we use a pressurized liquid nitrogen cryostat.
2.3.3. Sample tests

Preliminary tests were carried out with a reduced voltage of 50 V and 10 ms duration, in order to observe the first times of the current limitation. Fig 4 is a graph of the current and various electric fields measured along the CC. It shows an inhomogeneous phase during 5 ms and then a homogenization of the quench. The current peak ranging between 2 or 3 times the HTS critical current then its decreasing phase during a few milliseconds is the normal curve for a current limitation.

![Graph showing current and electric fields](image1)

Fig 4: FCL test at 50 V, 86 K and 10 ms

Thereafter, tests under 100 V and 150 ms were carried out to supply the CC with more important electric and thermal constraints (Fig 5). This test allows observing the current stabilization phase corresponding to the whole HTS normal state. We can notice that during this phase the dissipated energy density in the CC reached 450 J/cm3 with a CC average temperature at the end of the short-circuit of 250 K.

After this test, the temperature has been decreased to test the SCFCL at a lower temperature but the low homogeneity damaged the CC. The failure occurs essentially at the border of the coated (Fig 6). When an area switched to normal state, the current flowed from the shunt toward the stainless steel substrate. The contraction at the border of the superconducting film was not able to support such high current and burns.

![Coated conductor destruction](image2)

Fig 6: Coated conductor destruction after a limiting test at 84 K

3. Thermal phenomena

It is very important to study thermal phenomena in SCFCL, by using numerical models to calculate the maximum temperatures, simulation with FLUX2D [7] to understand thermal propagation and measurements to validate these models.
3.1. Numerical model

The resistive SCFCL operates with strong temperature rises. In this numerical model the temperature is considered homogeneous along the ribbon. Calculation of the temperature is:

\[
P_{sc} = L_{cc} \times I_{cc} \times \sum_{i} C_{p} \times \left( \frac{dT_{cc}}{dt} \right) \times \frac{dT_{cc}}{dt}
\]

“\(P_{sc}\)” the short-circuit power in W, “Cp” the ribbon specific heat in J/m³.K, “\(L_{cc}\)” and “\(I_{cc}\)” the length and width of the ribbon in m, “T” the ribbon temperature in K and “i” the different layers of the Coated Conductor. We can also calculate the maximum temperature “hot spot” reached after a test by using the current square measured and the linear resistance of the CC. We consider a ribbon cooled by a liquid nitrogen bath which temperature is constant. Exchanges with the cryogenic fluid are:

\[
P_{ex} = h_{N} (T) \times (T - T_{N}) \times A_{ex}
\]

“\(P_{ex}\)” power exchanged with nitrogen in W, “T” the ribbon temperature in K, “\(T_{N}\)” the temperature of the liquid nitrogen bath in K and “\(A_{ex}\)” exchange surface in m². “\(h_{N}(T)\)” is the liquid nitrogen heat transfer coefficient in W/m².K, shown in fig. 7.

Fig 7: Heat transfer coefficient function of the temperature difference

3.2. FLUX2D simulations

The simulation software FLUX2D enables us to study the thermal propagation in the sample according to various characteristics like the geometry, the thermal conductivities of materials and the heat exchange with liquid nitrogen. We have simulated the coated conductors with its layers and material properties under a current limiting test (Fig 8).

Fig 8: Thermal propagation simulation on FLUX2D software
3.3. Temperature measurement

We have deposited a parylene layer by CVD (Chemical Vapor Deposition) above the shunt and the substrate to isolate them from the deposited thermal sensors which is a coated Cu resistor deposited by Lift Off (Fig 9).

![Copper sensor deposited above the substrate](image)

**Fig 9**: Copper sensor deposited above the substrate

The sensor is a meander with a thickness of 300 nm and a width of 50 µm. It is divided in four parts, the total resistance of the sensor at 300 K is 308 Ω, measurements under various temperatures show a good linearity and a resistance at 77 K of 156 Ω. With a current supply about 10 mA, it is possible to measure a temperature variation of 1 K which is enough for the study.

3.4. Comparison

Numerical calculations and simulations under FLUX2D use the dissipated energy during the short-circuit and the heat exchanges with liquid nitrogen. Fig 10 shows a good correlation between these three temperatures, this validate our measurements and our models.

![Graph comparing calculated, simulated and measured temperatures](image)
4. Conclusion

These tests are very promising because the current limitation function is perfectly respected and operation close to the critical temperature allows improving the homogeneity problems often encountered in SCFCL. For the first time we could limit the current with an important energy density dissipated (450J/cm3) for a limitation duration (150 ms) sufficient to be switched by a protection apparatus. The measured, calculated and simulated temperatures are in good correlation, which validate our models and measurements. The use of the coated conductors for current limitation applications is possible, however it is necessary to understand the phenomena at the beginning of the quench. It should be noticed that the resistor at the normal state have to be increased to limit the current at lower values, so it is necessary to use longer CC or to decrease the thickness of the substrate (50 µm for example).

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