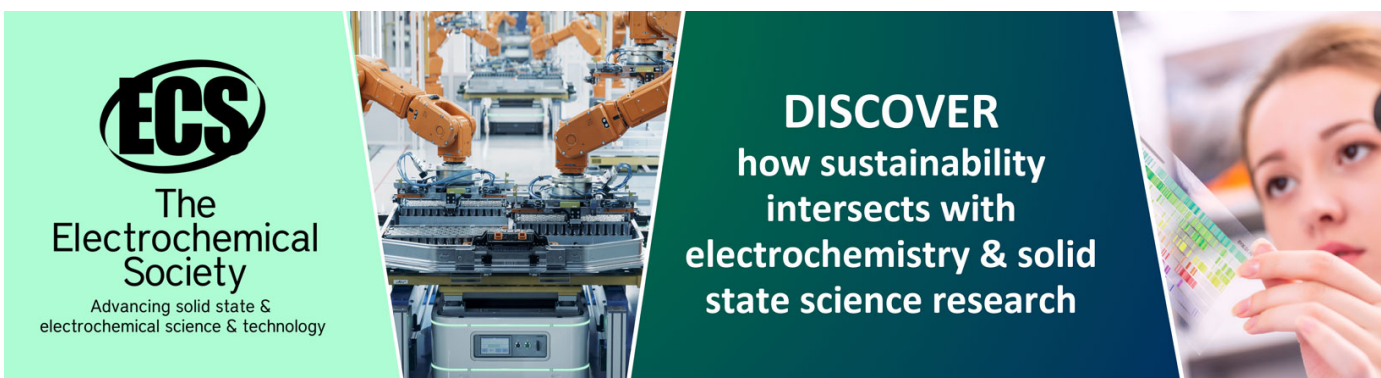# Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors

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Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors

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Abstract. A fault current limiter module for medium voltage applications has been built and tested successfully. The module corresponds to one phase of a 3-phase limiter for the 13 kV-class distribution voltage level. The resistive type limiter consists of 15 bifilar coils wound from a total of 15 x 50 m of AMSC's 344S superconductors, a commercially available second generation YBCO tape stabilized by stainless steel laminates. The module has a rated current of 300 Arms and a rated voltage of 7.5 kV corresponding to a nominal apparent power of 2.25 MVA. The cryostat is equipped with commercial current feed-throughs and the module is operated in liquid nitrogen at atmospheric pressure. For long term operation as a closed system a commercial cryogenic refrigerator coldhead is installed. Power tests and dielectric tests of the module have been performed at the IPH Berlin (Institut "Prüffeld für elektrische Hochleistungstechnik") up to prospective currents of 28 kA. In standard power tests at voltages up to 7.8 kV and fault hold times of about 50 ms an excellent limiting performance was observed both at various prospective fault currents and at different fault starting phase angles. Within a second experimental series, an appropriate shunt reactor was connected in parallel to the limiter. The benefit of this method is that the limited current can be adjusted to the customers needs and the required amount of HTS-wire can be also appreciably reduced. The setup of the module and the test results are reported.

1. Introduction

Due to the steadily increasing energy consumption the workloads of many of the existing grids in energy transmission and distribution tend to reach their limits in terms of short-circuit power. The ideal countermeasure is a fault current limiter (FCL) with an impedance near zero under normal operating conditions and a fast, self triggered transition to a high impedance state within the first millisecond after the occurrence of a fault in the grid. There are many activities worldwide on various types of superconducting FCL using different high temperature superconductors (HTS) like e.g. bulk BSCCO [1], BSCCO tapes [2] or YBCO coated conductors which are also called second generation (2G) HTS wires [2]. For a good overview of the state of the art see [4].

The most common type of superconducting FCL is the resistive type, which consists of an appropriate length of a superconductor directly installed in series in the grid. This type offers the advantages of fail-safety, compactness and low impedance during normal operation. A drawback is

that during a fault, a resistive FCL quenches and absorbs energy. Therefore, after each fault, the system needs a recovery time of at least a few seconds without current flow.

Soon after the discovery of HTS materials, Siemens started the development of resistive HTS-FCLs based on YBCO-thin films deposited on sapphire substrates. The superior limiting performance of this conductor type was demonstrated in tests of both a 1.2 MVA 3-phase AC model [5] and a 1 MVA DC model [6], but there was no perspective that the HTS conductor could be produced at economically acceptable costs.

With the advent of second generation (2G) of HTS-wires - the YBCO-coated conductors - the situation has changed, particularly with respect to economics. In 2005 AMSC and Siemens Corporate Technology started a strategic alliance to develop and explore the commercialization aspects of HTS fault current limiters made of 2G HTS wire. The first milestone in this project was a lab demonstrator with a nominal power of 120 kVA [7] and the second one is the demonstration of commercial grade performance in a medium voltage FCL module, which is the topic of this paper.

2. Design and setup of the module

The FCL module is a one phase resistive limiter in a modular design with a nominal voltage of 7.5 kV and a nominal current I_{nom} of 300 A_{rms}. In order to achieve a compact design combined with a low inductance, the switching elements are made of bifilar coils with an outer diameter of 50 cm, each coil consisting of 50 m of HTS-tape. The HTS-tape is AMSCs commercially available 344S conductor, a 4.4 mm wide YBCO RABiTS^{TM} tape with a thin silver cap layer and a 25 µm thick stainless steel tape soldered to both sides. Using a winding machine that controls the tension on the HTS tapes, the coils are wound with a constant distance of about 3 mm between neighboring HTS tapes, ensuring good access of the coolant LN_2 to the tape in order to minimize the recovery time. The wire proved to be very robust during winding.

As shown in figure 1 the FCL module is made of 3 stacks connected in series, each stack containing 5 coils connected in parallel. The size of the active part is about 40 cm × Ø 50 cm corresponding to a volume of 80 liters. The complete module had a resistance at 295 K of 10.4 Ω and a critical current I_c of 440 A at 77 K. It is equipped with a Gifford-McMahon refrigerator and commercial current feedthroughs as well as a pressure relief valve, a burst disc and pressure and LN_2-level sensors. As it was not clear from the beginning how much N_2 gas would be produced due to the heating during a power test, we installed two vent lines, each with a manual and an electrical valve.

Figure 1. Setup of the active part of the FCL module.

Figure 2. Fully assembled FCL module in the test cell of the IPH power testing lab in Berlin.

3. Test results

3.1. Single coil tests

The single coils were first checked for the room temperature resistance R_{295K} and the critical current I_c. The narrow ranges of $R_{295K} = 17.3\ \Omega \pm 5\%$ and $I_c = 92\ A \pm 8\%$ prove the stability of the 2G HTS wire production process. Subsequently each coil used in the module had to pass 20 switching tests at 2.3 kV, the maximum voltage available in the Siemens test lab. As this voltage is lower than the maximum voltage per coil expected in the power test of the complete module (~2.8 kV), the fault hold time Δt_{fault} was increased from the 50 ms standard to 90 ms in order to simulate the thermal load corresponding to 3 kV and 50 ms. At the end of a typical switching test, the resistance ratio R/R_{295K} reached about 125%. Extrapolating the measured R(T)-relation, one deduces a maximum average temperature of 115 – 125°C, which is at a safe level compared to the melting temperature of the solder in the wire.

3.2. Power tests of the FCL module

The power tests of the fully assembled FCL module have been performed at the Institut "Prüffeld für elektrische Hochleistungstechnik" (IPH) in Berlin, see figure 2. In total more than 40 power tests at voltages ≥ 6.5 kV have been performed. In all the tests the voltage was applied to the limiter for 40 to 50 ms depending on the phase angle at the start of the fault ϕ_{start}.

The cold head of the refrigerator was not operated during the tests, because the cooling power of the refrigerator is not designed for the high fault repetition rate during the power tests. Instead the cryostat was vented between the experiments and the system was refilled after approximately five switching events. In order to monitor the pressure rise during a fault the manual vent valves were kept closed and the electrical valves were closed 2 s before and re-opened 5 s after every fault. The pressure rise was measured and found to be below 400 mbar in all cases. This pressure range does not make special demands on the burst strength of the cryostat.

3.2.1. Tests in standard configuration. Two series of power tests at different prospective currents I_{prosp} of 10 kA_{rms} and 28 kA_{rms} were performed in the standard configuration with the FCL directly connected in series between the source and a shortened load. The values correspond to a percent impedance of 3% typical for medium voltage grids and a very low percent impedance of ~1%, respectively. At both prospective currents ϕ_{start} was varied in steps of ~15°. In Figure 3 the peak let-through current I_{peak} for both test series is plotted as a function of ϕ_{start}. I_{peak} reaches the highest values for ϕ_{start} between 60° and 90° and increases with I_{prosp}. For a typical grid with 3% impedance the
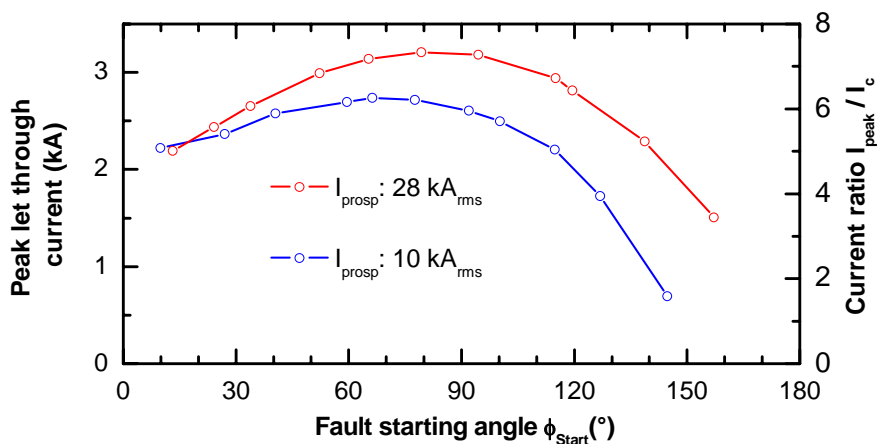

Figure 3. Peak let-through current as a function of fault starting angle, absolute values (left axis) and values relative to I_c (right axis).

maximum I_{peak} is 2.65 kA or $6 \times I_c$. The test with the highest I_{peak} (at I_{prosp}= 28 kA and ϕ_{start} = 75°) is shown in figure 4 with an expanded time scale for the first 2 ms: I_{peak} is 3.2 kA or $7.3 \times I_c$ and is reached 0.5 ms after start of the fault. The resistance ratio shown in the lower diagram reaches a final value of 110%, corresponding to 60 – 70°C average final temperature. The peak limited current in the last half cycle of all power tests ranged between 1 and 1.1 kA which is about $2.4 \times I_c$.
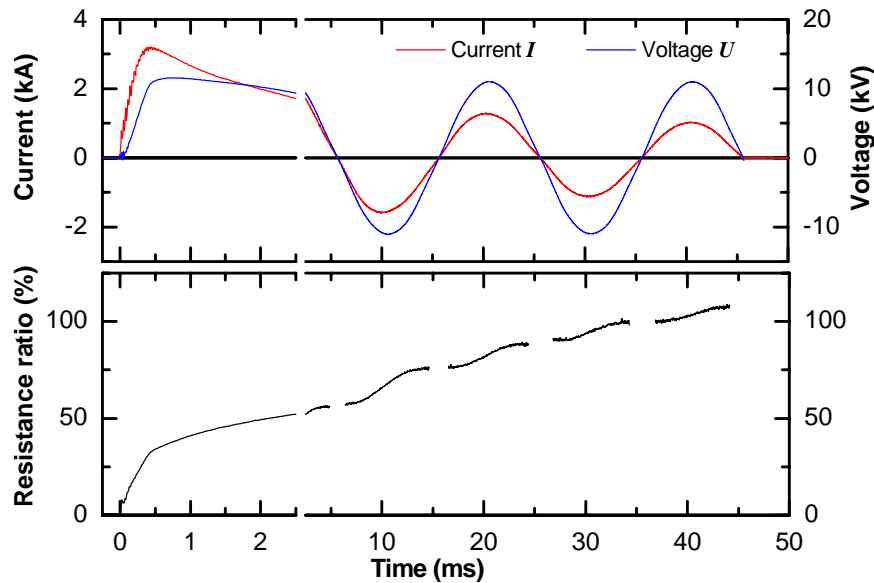

Figure 4. Power test in standard configuration, U_o: 7.8 kV, I_{prosp}: 28 kA$_{rms}$, ϕ_{start} = 75°.

3.2.2. Tests in a shunted configuration. The shunted configuration is particularly attractive for applications, where higher limited currents are desirable or acceptable. A FCL in series with a fast breaker S_1 is arranged in parallel to a current limiting shunt reactor, see figure 5. During normal operation S_1 is closed and the FCL shorts the limiting reactor; hence the grid features the desired low source impedance Z_{source}. In case of a fault the FCL trips, thus limiting the peak let-through current. Subsequently, S_1 is opened as fast as possible, mainly determined by the breaker's reaction time. The system now operates at the increased impedance $Z_{source} + Z_{shunt}$ and the correspondingly reduced fault currents. As the current through the FCL is already interrupted by the fast acting switch S_1 the time for opening S_2 can be adjusted, allowing for selectivity of the grid protection. Also, the FCL already can begin to recover. As soon as the FCL has recovered, S_1 can be closed and the system again operates at the low source impedance.
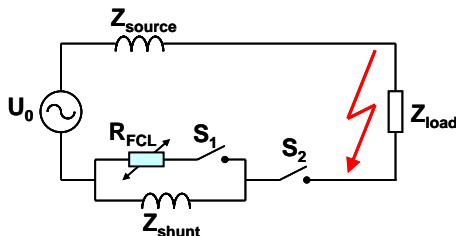

Figure 5. Scheme of a shunted limiter configuration.

Although the need for a reactor and an additional breaker seems at first to be drawback, this configuration offers several advantages:

- the limited current can be adjusted to the customers needs by selection of an appropriate reactor, therefore no major modification of the protection system is required
- during recovery or even during a failure of the FCL, the system continues operating at a reduced fault level

- the voltage across the FCL during a fault is only $U_0 \cdot Z_{shunt}/(Z_{source} + Z_{shunt})$ which is significantly lower than U_0 as long as Z_{shunt} is not much higher than Z_{source}. Consequently the FCL can be designed to be smaller and cheaper.

Three tests of this type were performed at $U_o = 8.3$ kV, $Z_{source} = 0.24\ \Omega$ and $Z_{shunt} = 0.26\ \Omega$; Figure 6 shows the test at $\phi_{start} = 0°$. In the upper diagram the total current I_{total} (in red), the current through the FCL I_{FCL} (orange) and the voltage at the shunt reactor U_{shunt} (blue) are plotted. As expected for an asymmetrical switching operation the fault current rises to a peak (44 kA in this case) before it stabilizes at ~16.4 kA_{rms} which is roughly half of the prospective 34 kA_{rms}. As I_{FCL} is negligible compared to I_{total}, the system behaves as if the shunt reactor would be inserted instantaneously into the circuit at the occurrence of a fault. The diagram in the middle shows I_{FCL} in more detail and U_{FCL} which is identical to U_{shunt} as long as the switch S_1 is closed. As Z_{shunt} is roughly equal to Z_{source} the voltage across the FCL is 4.3 kV, hence about 50% of the source voltage. The maximum value of R/R_{295K} in the lower diagram is 70% and confirms that the load on the FCL is much smaller than in the 7.8 kV switching tests in standard configuration, where R/R_{RT} reached ~110%. This proves that the active part of the FCL can be designed to be significantly smaller if a shunt reactor is connected in parallel to the FCL.
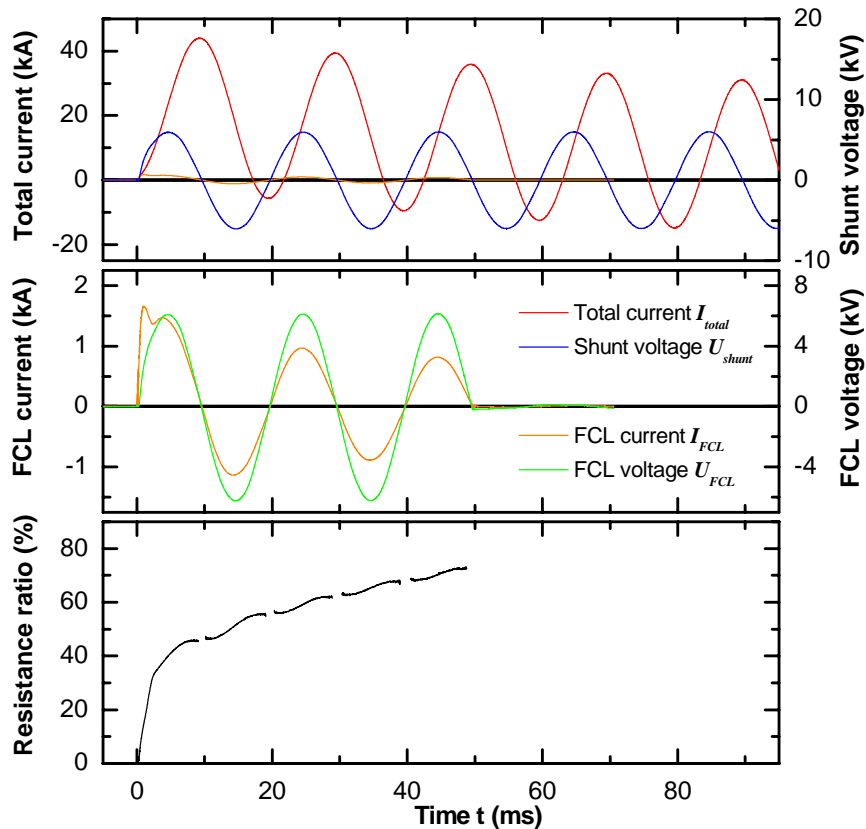

Figure 6. Power test in shunted configuration, U_0: 8.3 kV, I_{prosp}: 34 kA_{rms}, $\phi_{start} = 0°$.

3.3. Recovery after a fault

An important characteristic of a FCL is the time it must be disconnected from the grid in order to re-cool after a fault. The condition for recovery is met if I_{nom} can be applied without a measurable voltage drop across the switching elements, which means that the wire has recovered to the superconducting state. Experiments with various time intervals Δt_{rec} between fault and application of I_{nom} were performed. For comparing purposes the recovery tests were done at a voltage of 6.55 kV leading to a resistance ratio of 100%, i.e. heating up to 295 K as average final temperature. In the test for $\Delta t_{rec} = 2.4$ s shown in figure 7 no voltage across the FCL can be observed during application of I_{nom}. The

recovery time of 2.4 s is the same for single coils, indicating that the dense stacking of coils in the fully assembled module does not increase the recovery time.
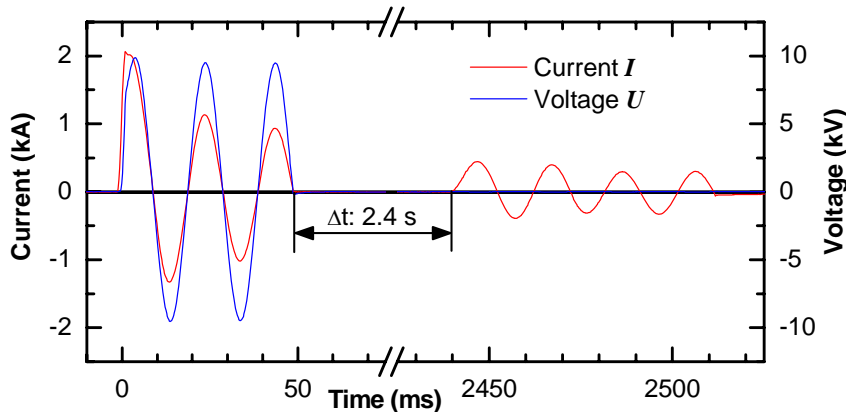

Figure 7. Demonstration of recovery time.

3.4. Dielectrical tests

Additionally basic insulation level (BIL) tests of the standard rated lightning impulse and power-frequency withstand voltages have been performed. The insulation between the active part of the FCL and the grounded vessel was successfully tested at >95 kV (15 pulses 1.2 / 50 μs in both polarities) and at >38 kV (1 min, 50 Hz). These are the standard BIL levels for nominal voltages up to 17.5 kV.

4. Summary and outlook

A medium voltage FCL module was constructed from a total of 750 m of AMSC's 344S superconductors, a stainless steel laminated 2G HTS wire. It has successfully passed more than 40 power tests at voltages between 6.5 and 7.8 kV up to prospective currents of 28 kA and various percent impedances down to ~1%. The maximum peak let-through current observed was about $7 \times I_c$ and the typical limited current at the end of the fault hold time is about $2.4 \times I_{nom}$. Additionally the shunted limiter concept was demonstrated with the advantages of compatibility with existing protection systems, continued operation during recovery or failure of the FCL and the option to make the FCL smaller and cheaper due to the reduced load on the FCL. The insulation between the active part of the module and the grounded vessel passed the standard rated lightning impulse and power frequency withstand voltage tests for nominal voltages up to 17.5 kV.

Recently AMSC won a DOE project to develop and perform in-grid testing of a three-phase 115-kV FCL using the company's 344S superconductors. In this project Siemens will be the partner to design and build the active part of the limiter. The team also includes Nexans, the University of Houston and Los Alamos National Laboratory.

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