Abstract

Within a collaboration of American Superconductor, Siemens, Nexans and Southern California Edison one electrical phase of a resistive superconducting fault current limiter for the 115 kV transmission voltage level has been designed and manufactured. The active part of the limiter consists of 63 bifilar coils made of 12 mm wide steel-stabilized YBCO conductor and is housed in a cryostat operated at 5 bar and 74 K. The first phase was completely assembled and successfully subjected to power switching tests and high voltage tests. The basic design of the system and the test results are reported. The work was funded in part by US-DOE under Contract Number DE-FC26-07NT43243.

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1. Introduction

The need for control of the increasing fault currents in transmission and distribution networks is the reason for the worldwide activities in the development of various types of fault current Limiters (FCL) [1-5]. The goal of the project described in this paper was the design, manufacture and test of a transmission voltage (115 kV) resistive FCL based on 2nd generation HTS wires. The partners and their responsibilities within the project are: American Superconductor (AMSC) for project lead, production of wire, cryostat design and system integration, Nexans for design and manufacturing of high voltage terminations and
their connection to the limiter, Siemens for the design and manufacturing of the active part of the limiter and Southern California Edison as the partner for installation and on-site testing. The first project phase mainly comprised the development of a 12 mm wide stainless steel stabilized YBCO wire, the design and test of bifilar coils as switching elements and the manufacture and test of the terminations. It was completed by the successful switching and high voltage tests of the so-called subscale module consisting of 6 full-size coils arranged in series [6]. In phase two of the project one complete electrical phase was constructed and subjected to high power switching tests as well as high voltage tests at the Powertech Labs Inc. in Surrey, BC, Canada. The system design and the test results will be reported in this paper.

2. Specifications and design

2.1. System design

The basic specifications for the planned three-phase FCL prototype system are given in fig. 1a. and the basic design features (shown in fig. 1b) are:

- one cryostat per phase, 11 m long, 2 m outer diameter
- a closed loop cooling system with sub-cooled operation at 74 K and 5 bar
- high voltage terminations at both ends
- a shunt reactor in parallel allows to adjust the limited current to the customer’s requirements. Due to the shunt reactor the voltage across the FCL is reduced by ~40% during a fault.

| Requirement                   | Prototype System | Production Units |
|-------------------------------|------------------|------------------|
| Nominal Voltage               | 115kV rms        | 115-138kV        |
| Insulation Class              | 138kV            | 138kV            |
| Nominal Current               | 900A             | >2,000A          |
| Maximum Site Unlimited Fault Current | 63kA       | >80kA            |
| Site Limited Current          | 40kA             | As required by customer |
| Trip Current                  | 1.6pu            | As required by customer |

Fig. 1. (a) Basic specifications of the FCL systems. (b) Sketch of the overall FCL system set-up with basic design features.

Before setting up the complete three phase system, one electrical phase has been manufactured and tested during the running project to allow for possible improvements and redesign depending on the test results. This first electrical phase comprised a cryostat with sub-cooler supplied from a liquid nitrogen tank, two terminations, and a superconducting switching module.

2.2. Design of the switching module

The switching module is a horizontal stack of 63 pancake coils resting on a total of six two-legged supports. The stack is arranged as a series of 21 sub-modules each consisting of 3 coils connected in parallel (fig. 2a). The basic switching elements are bifilar coils wound in a two-in-hand configuration (fig.
with an outer diameter of 50 cm and an axial length of 5 cm. Each coil is made of \(2 \times 27\) m of YBCO coated conductor fabricated by AMSC. The conductor is a 12 mm wide 3-ply wire with two stainless steel laminates and has a spirally wrapped PTFE adhesive insulation for a high inter-turn voltage withstand. The average critical current \(I_c\) at 77 K is more than 250 A for the 27 m pieces. An \(I_c\)-criterion of \(0.1 \mu\text{V/cm}\) (i.e. 2.7 mV over 27 m wire length) was chosen to avoid quenching of the wires during end-to-end \(I_c\)-measurement. Each coil was subjected to extensive qualification tests including 32 power switching test and a final \(I_c\) test. The nominal apparent switching power of the module is \(30.9 \text{kV}_{\text{rms}} \times 1.35 \text{kA}_{\text{rms}} = 42\) MVA.

![Image](image_url)

**Fig. 2.** (a) Modular arrangement of the \(21 \times 3 = 63\) coils. (b) Sketch of the two-in-hand coil configuration.

### 3. Power switching tests

#### 3.1. Switching test set-up

According to the specifications in fig. 1 the single phase system has been designed for a source voltage (phase to ground) of \(115\) kV / \(\sqrt{3} = 66.4\) kV and a prospective short circuit current of 63 kA. The specified limited current was 40 kA. Due to this high limited to prospective current ratio, the major part of the source voltage drops across the source resistance in case of a fault, while the voltage drop across the limiter is only about 28 kV. In order to test the complete parallel configuration of shunt and FCL a huge power in the range of GVA (28 kV \(\times\) 40 kA) has to be provided by the power lab. However, most of the fault current is flowing through the parallel shunt reactor. Therefore the FCL is tested without the shunt by applying the same voltage of 28 kV giving a maximum limited current of only 4 kA_{rms}.

Numerical simulation of the behaviour of the FCL shows that the stress on the switching module is similar in both cases. The tests were performed in the open air part of the high power lab of Powertech Labs Inc.

#### 3.2. Switching test results

In total the FCL passed 30 power switching tests at voltages between 10 and 30 kV, at various prospective fault currents between 19 and 60 kA, at various phase angles at the start of the fault and for various fault durations. In the first series of tests the source voltage was increased from 10 to 30 kV. As an example fig. 3 represents the switching behavior for an asymmetric fault at the full voltage of 30 kV for a prospective fault current of 19 kA_{rms} and a fault duration of 3½ cycles. The diagram shows the
voltage at the FCL in blue, the limited current in green and the prospective current calculated from Powertech data in red. In this case the fault current is reduced by 84%, i.e. from 58 kA_{peak} to 9.3 kA_{peak}.

Two series of tests with a variation of the phase angle at the start of the fault $\phi_{\text{start}}$ have been carried out, one series at the maximum prospective fault current that Powertech could provide for the nominal voltage of 28 kV and another one for the maximum voltage (10 kV) that Powertech could provide for a high prospective fault current of 60 kA. The current and voltage traces for the series at 28 kV / 20 kA are shown in fig. 3b.

Another series of tests was performed to determine the recovery time, i.e. the time span the current has to be switched off after a fault before the FCL is operational again. This time span mainly depends on the energy dumped during a fault and is typically in the range 20 to 30 s. To determine the recovery time the rated current is re-applied to the FCL at a certain time after the end of the fault. Fig. 4a shows an example for such a test. In this case 20 s after the end of a 3-cycle fault the rated current is applied to the FCL. The voltage during this last period is only approximately 5 V_{rms} and is not increasing, thus indicating that the FCL has essentially recovered after 20 s.

Finally an experiment was made demonstrating that the FCL can handle two faults within a 1 min time interval. The diagram in fig. 4b shows current and voltage during this experiment. Obviously the behavior before and during the fault is exactly the same for the two faults confirming that during a fault the
temperature rise of the LN\textsubscript{2} in the cryostat is low enough to allow for several faults within short time intervals. It also confirms that the FCL has completely recovered during 60 s.

3.3. Benchmark tests

As it was not possible to check the critical current during the power tests for potential degradation, a so called benchmark test was performed before and after every series of measurements. In a benchmark test an AC-current with amplitude of roughly 2 times the expected \(I_c\) was applied for 2 cycles. Fig. 5a shows an example for such a test. The dark blue plot is the measured voltage and the light blue is the voltage corrected for the inductive portion.

From the first quarter cycle of each of these benchmark tests the corrected \(U(I)\)-curve is extracted and plotted in fig. 5b. The variation of the benchmark current taken at 1 mV/cm is less than 10\% and can be attributed to the temperature variations in the range of 72 to 74 K. Although the sensitivity of such a test is much less compared to a normal \(I_c\) test applying a 1 \(\mu\)V/cm criterion, it gives an indication that there was no severe damage caused by the switching experiments.

4. High voltage tests

The sequence of high voltage tests is listed in table 1. The most important tests were the power frequency test per IEC 60840 at 190 kV\textsubscript{rms} for 15 min, the lightning impulse test per IEC 60840 at 650 kV (1.2 / 50 \(\mu\)s) and the switching impulse test per IEEE C57.16 at 540 kV (250 / 2500 \(\mu\)s). All three tests were performed in a first run with both terminals connected to the source and in a second run with only one terminal connected to the source. This demonstrates that the internal arrangement does not lead to over-voltages due to reflections at an open terminal. Before, between and after these two test series a partial discharge measurement was made in order to confirm that no degradation of the dielectric had occurred. At the very end another power frequency test at 190 kV\textsubscript{rms} was performed for 30 min followed by a high voltage soak at 80 kV\textsubscript{rms} for 15 hours. The system passed all these tests successfully.

5. Summary

Within phase 1b of a DOE-funded joint project lead by AMSC and including Siemens, Nexans and Southern California Edison, one electrical phase of a resistive superconducting FCL for the transmission
voltage level of 115 kV has been designed, manufactured and tested. The system successfully passed 30 power switching tests at voltages up to 30 kV and prospective currents up to 60 kA. Likewise all high voltage tests including power frequency as well as lightning and switching impulse tests at 190 kV_{rms}, 650 kV_{peak} and 540 kV_{peak}, respectively, have been passed without failure.

Table 1. Sequence of the high voltage tests performed. All test were passed successfully.

| Test | Main parameters tested | Termination Configuration | Results |
|------|------------------------|---------------------------|---------|
| 1 | Partial discharge test per IEC 60840 | Measurement at 114 kV (after few min. at 140 kV) | Both terminations connected to source | No detectable PD at 114 kV test passed |
| 2 | Power frequency-voltage test per IEC 60840 | 190 kVrms / 15 minutes | Both terminations connected to source | test passed |
| 3 | Lightning impulse voltage test per IEC 60840 | +/- 650 kV shots 15 shots each polarity | Both terminations connected to source | test passed |
| 4 | Switching impulse test per IEEE Std. C57.16 | +/- 540 kV | Both terminations connected to source | test passed |
| 5 | Repeat partial discharge test | Measurement at 114 kV (after few min. at 140 kV) | Both terminations connected to source | No detectable PD at 114 kV test passed |
| 6 | Repeat Power frequency-voltage test per IEC 60840 | 190 kVrms / 15 minutes | Both terminations connected to source | test passed |
| 7 | Repeat Switching impulse test per IEEE Std. C57.16 | +/- 540 kV 15 shots each polarity | One termination connected to source. | test passed |
| 8 | Repeat Lightning impulse voltage test per IEC 60840 | +/- 650 kV shots 15 shots each polarity | One termination connected to source. | test passed |
| 9 | Final partial discharge test | Measurement at 114 kV (after few min. at 140 kV) | One termination connected to source. | No detectable PD at 114 kV test passed |
| 10 | Power frequency-voltage test per IEC 60840 | 190 kVrms / 30 minutes | One termination connected to source. | test passed |
| 11 | High Voltage Soak test | 80 kVrms / 15 hours. | One termination connected to source. | test passed |

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