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Testing and Demonstration Results for the Transmission-Level (138kV) 2G Superconducting Fault Current Limiter at SuperPower

(Published under the title: Recovery Under Load Performance of 2nd Generation
HTS Superconducting Fault Current Limiter for Electric Power Transmission Lines)

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***Abstract* —Development of Superconducting Fault Current Limiters (SFCLs) has been pursued for decades [1-4] and has been limited thermally and/or mechanically by the available superconducting materials performance characteristics [5]. However, within the past few years a newer, more robust type of superconductor known as 2G HTS wire, has become available in sufficient quantity and lengths for developers to build prototype devices and test their capabilities. This new material has re-invigorated the worldwide race to develop a successful SFCL device that will meet the stringent demands of the electric utility application.**

SuperPower is pursuing the development of a transmission level (138kV) SFCL based on its proprietary 2G HTS wire and SFCL technologies. This paper will discuss testing and improvements made to optimize Recovery Under Load (RUL) performance. We also discuss low and high power tests and the influence of the different variables that have an important impact in RUL. A wide operating RUL window has been tested in order to define where RUL is feasible.

***Index Terms* — Fault current limiters (FCL), high-temperature superconductors, quench current, quench time, second generation high-temperature superconducting wires (2G HTS conductors), superconducting fault current limiter (SFCL)**

I. INTRODUCTION

WITH the dramatically increased demand on electric power, new power generation is being added and the power delivery networks are being upgraded. The levels of fault currents from events such as lightning striking a power line, or downed trees or utility poles shorting the power lines to ground, can increase beyond the capabilities of the existing equipment, leaving circuit breakers in an “over-duty” condition. Fault-current limiters (FCL) using high temperature superconductors offer a solution to control fault-current levels on utility distribution and transmission networks [1-5]. SuperPower, Inc. and its research partners, including American Electric Power (AEP), have been working on a three-phase program to develop a practical SFCL to meet the needs of the utilities.

SuperPower, Inc. is developing a 138kV SFCL with RUL. Although RUL is very challenging, it is desirable from the utility’s perspective since the device can recover to the low impedance state without having to be taken off-line. Since the SFCL device does not switch in and out of the circuit there will be less stability control issues during transients. Additionally since they do not require an active control system, an RUL-enabled device has better performance characteristics and is less complex which; typically translates into higher reliability than other approaches.

In order to achieve RUL, a number of challenges must be overcome by the SFCL design and wire used. In resistive SFCL’s, the superconducting material quenches after the occurrence of a fault. If RUL is required, the quenched superconducting material must be able to cool while still carrying a fraction of load current until the 2G wire again becomes superconducting. The time taken by the superconducting components to recover to their initial temperature defines the recovery time. This time is very important, since SFCL devices used in distribution or transmission lines may be subjected to several faults in short periods of time. When RUL is used, the design and characteristics of the SFCL system are critical to determining the overall time taken to recover either under load (RUL) or no load (Non-RUL) modes. We focused our efforts to improve several key components of the design that affects the recovery time and therefore the overall performance of the system. A key element driving the performance of a SFCL is the 2G wire. Some of the relevant features of 2G HTS conductors may provide solutions to those challenging issues:

(1) High n-values (20-40) that limit the fault current faster;
(2) 2G HTS conductors in 1000+ m length [6-8];
(3) Superior electro-mechanical properties [7-8];
(4) Higher critical currents, recently achieved 1000A/cm,
all seem to help during the recovery process.

We will show the impact of some of the variables discussing the correlation to recovery time with and without load current.

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II. EXPERIMENTAL SETUP

The schematic diagram of the test circuit for a series of fault current tests is shown in Fig. 1. The fault current limiting modules consist of a set of 12 mm wide 2G HTS tapes in parallel with a copper wound shunt coil. At SuperPower, we can test faults up to 7kA and load currents up to 700A peak. The system voltage is provided by an isolation transformer that has primary 208 VAC and variable secondary 5/10/20/40 VAC, 60Hz. Shunt impedance is variable keeping an X/R ratio of 30. The current leads, HTS material and shunt coils are immersed in liquid nitrogen (LN2) during the test.

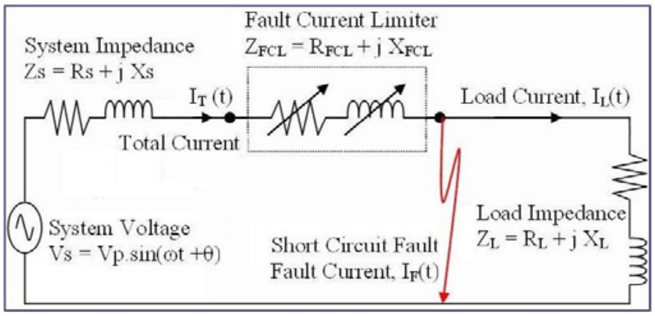

Fig. 1, Schematic diagram of single-phase power system representation.

The short circuit faults were generated and controlled by a bipolar thyristor switch. The voltage and current waveforms were recorded by a LeCroy *WaveRunner* 6050A Oscilloscope through LeCroy AP031 Differential Probes and PEM CWT30B Rogowski Current Waveform Transducers, respectively.

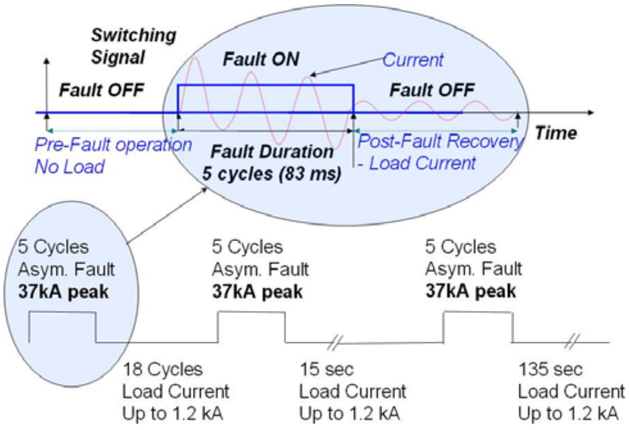

Fig. 2. AEP reclosure sequence for the first (3) faults.

Larger modules were tested at an outside high-power test facility with faults up to 37kA asymmetric peak and loads up to 1200A$_{rms}$ current. The faults and loads were applied following the AEP reclosing sequence shown in Fig. 2. The HTS material must be able to recover after a fault while the load current is still flowing through the circuit. This recovery process is what we call recovery under load. Due to the proximity in time between the three first faults of the AEP reclosing sequence and the short time between them for the SFCL to recover from each fault, the worse case scenario for RUL is found between the second and the third faults of Fig 2.

In addition to the AEP sequence, a stuck breaker scenario must be considered that may last an additional 11 cycles after any of the individual 5 cycle faults. In order to test our device under the worst case conditions, the duration of the faults varied from 5 to 26 cycles. The total of 26 cycles corresponds to the three first 5 cycle faults of the AEP sequence, together with the 11 cycles of fault of stuck breaker. RUL for 26 continuous cycles of fault tested at SuperPower is shown in Fig.3, a load of 230A peak is recovered in 1.75 sec.

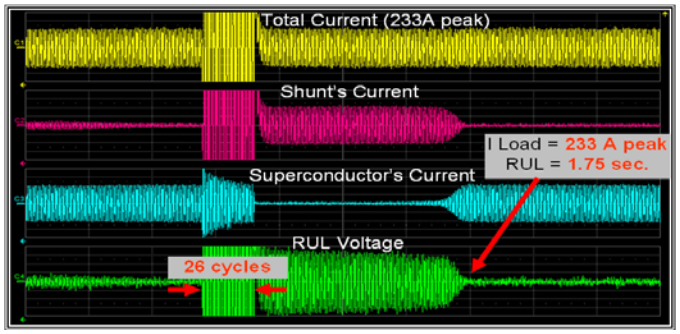

Fig. 3. Tape tested with 26 cycles of fault, recovering 230A peak in 1.75 sec.

III. RECOVERY UNDER LOAD

Several improvements have been made in RUL, especially in the interconnection between the superconductor and the copper connectors. Fig. 4 shows the temperature distribution on the superconductor under a fault of 37kA peak for two different connector designs. The temperature scale in both graphs is the same, but the magnitude of the temperature distribution at the left contact is higher than the one at the right. A number of different connectors have been tested and analyzed. Testing of these connectors has shown very different recovery times and maximum load current magnitudes able to be recovered.

For instance, at the bottom of Fig.4 we can see two different recovery RUL behaviors. In both cases we drive a typical 5 cycle fault of 5kA peak with a 80A peak load current, but using two different connector designs. The RUL shown at the bottom left was taken using baseline design connectors, showing a recovery time of 56 seconds. However, the RUL shown at the bottom right was taken using improved connectors. In this case the RUL time was reduced to approximately 2.8 seconds under the same test conditions. Notice that there is a difference time scale between both diagrams, having the graph at the left 10 seconds per division versus 1 second per division at the right.

Consequently, there exists a significant difference in the recovery time and the maximum load current able to be recovered under the same conditions with different contact geometries. This seems to be one of the major limiting factors driving RUL.

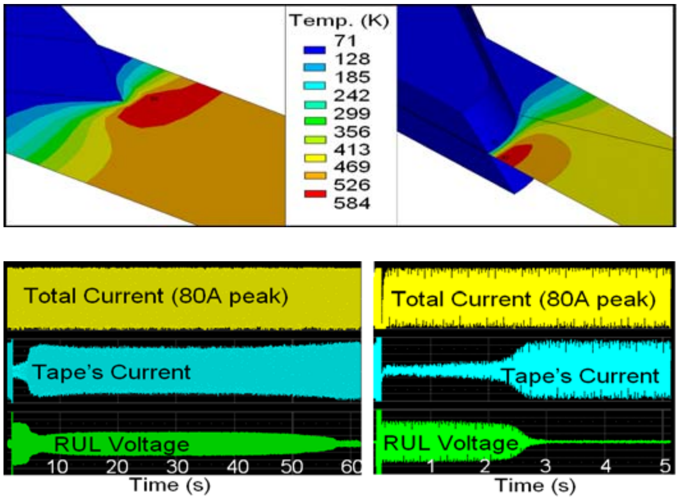

Fig. 4. Top, temperature distribution between the connector and the superconductor interconnection under fault conditions. Bottom, recovery time for a typical contact at the left and an improved contact at the right.

Other factors such as the load current and load voltage have an important impact in RUL. Of course, the amplitude and duration of the faults and their frequency of appearance impact RUL. However, in this study we focused on RUL under the exact conditions that an SFCL must face for the American Electric Power (AEP) reclosure sequence. For this reason we followed the AEP standards, shown in the AEP sequence in Fig.2, paying special attention to the worse case scenario found between the second and third faults. The duration and frequency of repetition of the faults as well the load time frames between faults are given in this graph. In order to study the influence of the load current and voltage versus the fault during the recovery process, we kept constant the fault magnitude for a number of different levels of load currents and voltages.

Making a comparison between recovery without load current and recovering with load current, we can clearly see in Fig. 5 that under the same conditions, without load current the recovery time is very fast, about 3.2 seconds, but recovering with a load connected, the same system after 110 seconds still does not recover under the load.

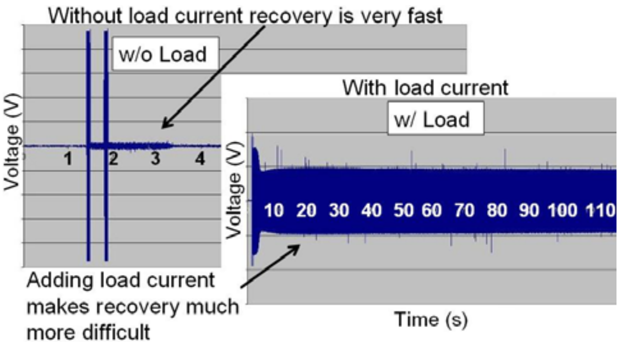

Fig. 5. Recovery time and voltage without load versus with load current.

Similarly, RUL time increases when the voltage per length in the superconductor is increased. Fig. 6 illustrates the recovery time with the same system for a base line voltage, 150% and 300% voltage increase showing recovery times of 3.5 seconds, 5 seconds and >110 seconds respectively. Hence, the voltage per unit length in the superconductor has also a direct impact in recovery under load. We have tested a number of different 2G conductors with different Ic's ranging from 150-400A, showing a higher percentage of recovered current in those having higher Ic values. SuperPower has been able to demonstrate high performance 2G wire capable of handling 1,000 A in 12mm widths which may have significant advantage in the SFCL application [8].

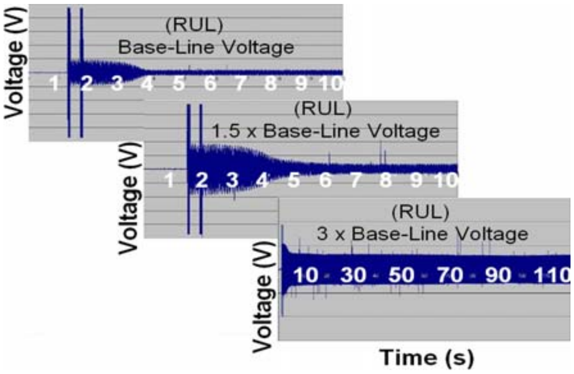

Fig. 6. Recovery under load for base-line voltage, 150% and 300%.

IV. High Power Test Results and Discussion

Two prototypes were tested at an outside high-power test facility with faults up to 37kA asymmetric peak and loads up to 1200A rms current. At the left of Fig.7 is shown the test module that we used to test RUL. At the right of Fig.7 is illustrated the magnetic field distribution of a matrix setup composed of multiple 8 tape modules. At the top left corner, an 8 tape module was highlighted with a circle.

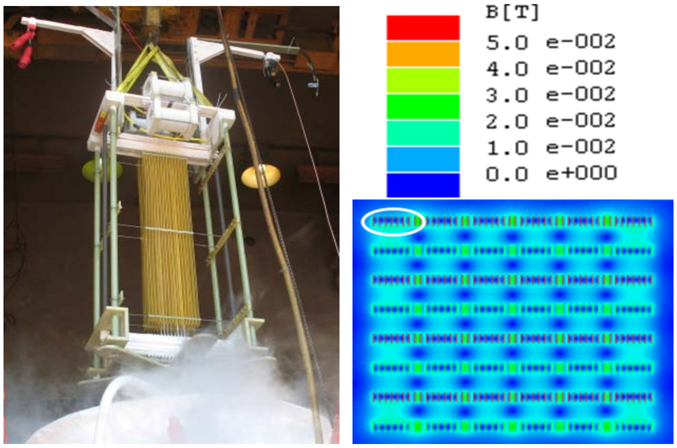

Fig. 7. At the left, the test module during testing at the outside power test facility. At the right, magnetic field of a matrix composed of 48 x 8 tape modules.

All the tests and results shown were taken in open bath, which is the worst case scenario for heat transfer under LN2. Optimal bath conditions are expected to increase RUL performance on the order of 20 -30%.

Two different sets of high power tests were performed at the power test facility. In the first set of tests, our objective was to achieve RUL for a proposed application at the AEP TIDD substation following the AEP reclosing sequence. In the second set, our goal was to test a wide range of the variables impacting RUL to define its feasibility and performance. An example of the tests performed to achieve RUL for the TIDD substation with the AEP sequence is shown at the left of Fig. 8. This graph illustrates the current flowing through the shunt coil, recovering around 90% of the total power between the second and third faults of the AEP sequence. However, with optimal bath conditions (pressurized, subcooled), fully recovery is expected between the second and third faults.

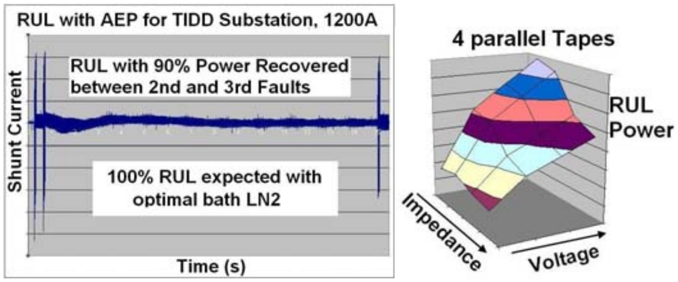

Fig. 8. On the left, RUL following the AEP sequence for TIDD substation. On the right, recovered power in 4 tapes versus voltage and impedance.

Once we obtained all the RUL operating points, we defined different mapping surfaces where RUL is achievable versus the variables driving its performance. At the left of Fig.9 is illustrated the maximum recovered current versus the impedance, voltage and groups of different number of tapes. At the right is shown the maximum recovered current per tape, impedance, and voltage for each group. The maximum current recovered per tape is quite constant for all the three groups of tapes. This mapping provides us the ability to predict RUL over a wide design space. Therefore, we can design any system to RUL for a wide range of load current/voltage at specific times following AEP. Using this tool, we can redesign to fully recover for the TIDD substation after the second or third fault.

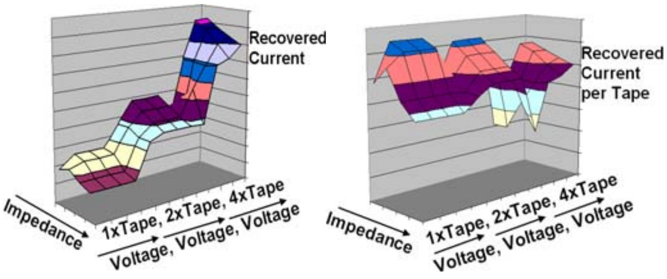

Fig. 9. On the left, maximum recovered current per group of tapes, impedance, voltage and impedance. On the right, maximum recovered current per tape, impedance, voltage and impedance.

V. CONCLUSION

Optimized connectors have shown a superior performance over conventional connectors. The variables driving RUL have been identified and studied in detail. RUL mapping will provide us the ability to predict RUL over a wide design space. The performance obtained at the high powered test facilities satisfies AEP's requirements for 37 kA peak limiting the fault in a 40% achieving RUL for the TIDD substation. Thus Alpha prototype for 138 KV transmission lines can be designed for RUL using 2G SFCL. Further optimization on the bath conditions and 2G HTS conductor structure such as stabilizer and substrate, and assembly structure will yield better performance for RUL. Recovery under load can be also optimized by using higher Ic superconductors able to recover higher load currents. This provides the ability to use less superconducting material, reducing the overall volume of the device, cryogenics and overall conduction losses. Currently 2G superconductors are available in lengths up to 1000 meters, reducing the number of connections in the devices, as well the resistive losses associated with them. Although RUL is very challenging, it is the most robust and feasible alternative since it is not affected by stability control during transients and it does not depend of any other series of elements that will decrease the performance and reliability.

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