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Hybrid superconducting fault current limiting CORC® wires with millisecond response time

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Abstract

The extensive development of Conductor on Round Core (CORC®) cables and wires has resulted in round, multi-strand, high-temperature superconductors (HTS) with engineering critical current densities (J_e) over 200 A mm^{-2} at 77 K, or over 800 A mm^{-2} at 50 K when cooled with cryogenic helium gas. The inherent fault current limiting (FCL) capabilities during direct current operation of a short kA-class CORC® wire of less than 4 mm in diameter are demonstrated in liquid nitrogen, developing nearly instantaneous voltages in excess of 20 V m^{-1} that increased to about 70 V m^{-1} within 15 ms of applied overcurrents up to 250% of the critical current (I_c). The CORC® wire response time and reactive voltage is comparable to that of a single tape, but at a much higher critical current and without the risk of burnout. The performance of the 0.15 m long CORC® wire remained unchanged after close to 100 overcurrent events with peak dissipation of 150–190 kW m^{-1}. Each event in which a total energy up to 1.4 kJ m^{-1} was dissipated in the CORC® wire resulted in a rapid heating followed by a subsequent thermal quench. The significant challenge to remove the heat from the FCL cable after a fault has cleared when cooled with helium gas in future naval power cables is addressed. Operation of the CORC® FCL conductor in stand-alone operation and operated as part of a hybrid-cable system, in which the overcurrent is instantly redirected to a normal conducting path outside of the cryogenic environment, is demonstrated without any degradation of the CORC® wire performance. The results show that highly flexible CORC® wires offer a straightforward path to safely increasing the operating current of FCL conductors beyond that of single tapes, without compromising their response time and voltage, while potentially allowing fast recovery times even when cooled with cryogenic helium gas.

Keywords: FCL, CORC, fault current limiter, SFCL

(Some figures may appear in colour only in the online journal)

1. Introduction

Next generation electric power systems require higher capacity, efficiency, and stability to meet the demands of increasingly complex grid systems. High-temperature superconductors (HTS) provide attractive solutions to stringent operating requirements, including the ability to protect electric power apparatus and systems from large currents that will be generated during a fault. As electric power distribution networks become more complex, various system components are increasingly at risk to the damaging effects of excessive currents that can occur in fault conditions. This is because increases in power demand are typically met with increases in power generation, addition of parallel conducting paths, and increases in interconnects within grid systems. Isolation devices such as circuit breakers are needed to provide active protection of crucial systems within power distribution networks when faults occur. The interruption capabilities of traditional protection devices are not necessarily scalable to the large fault currents in some existing networks and future power distribution networks, particularly for direct current (DC) systems [1–4]. This presents a need for superconducting cables that can effectively respond to fault currents by introducing an instantaneous impedance into circuits to limit the fault currents to levels that will not damage crucial components [5–7]. Superconducting fault current limiters (FCL) operate by exploiting the nonlinear superconducting-to-resistive phase transition that occurs when a superconductor is exposed to overcurrent (current in excess of the critical current, I_c).

Superconducting FCL systems have been extensively investigated and tested primarily for AC power networks, having recently been introduced into the market, typically as modules with their own associated costs and specifications per application [8, 9]. The development of long-length superconducting power transmission or distribution cables has been ongoing with several demonstration projects [10, 11], and the design of such cables to limit fault currents has been proposed and demonstrated [12, 13]. However, there are few demonstrations of FCL cables for DC power networks in which superconducting cables are effectively utilized [14]. Such networks are becoming increasingly viable with advances in power-electronics and are well suited for distribution applications such as those in wind-farms, naval ships, and electric aircraft. Circuit breaking within medium to high voltage DC systems with expected high currents during faults tends to be a larger challenge than for AC applications since there is no zero cross-over point in the power line at which mechanical switches can be opened.

Advanced Conductor Technologies, LLC (ACT) has been developing HTS Conductor on Round Core (CORC®) power cables [15] and wires [16] wound from superconducting RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) tapes. The CORC® power cables are the smallest and most flexible high current (far exceeding 1 kA) HTS conductors on the market. CORC® conductors can be designed to limit the current passing through them to a designated value by quickly developing a significant voltage when a fault occurs. FCL HTS power cables can thus be developed to protect electrical equipment against overcurrent, which significantly reduces the requirements of these devices and allows for a rapid recovery to the operational state as soon as the fault has cleared. FCL operation in a CORC® cable has previously been demonstrated in a cable that contained a relatively high amount of stabilizing material, resulting in a relatively slow response to overcurrent [15]. The CORC® cable was cooled with cryogenic helium gas, resulting in a significant recovery time after the fault had cleared. Because of their small size and low weight, CORC® FCL conductors can be further optimized with a very low heat capacity and limited electrical stabilization, which limits fault currents in very short timeframes and at relatively low overcurrent values. Recovery time needs to be reduced significantly when cooling the FCL cable with cryogenic helium gas to make CORC® FCL conductors viable for naval applications that will not allow use of liquid cryogens.

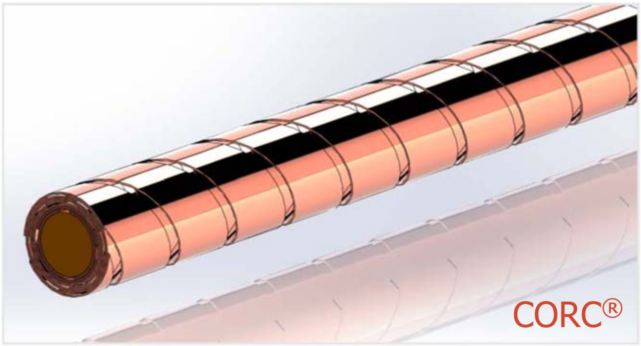

Figure 1. Overview of a CORC® conductor showing the metallic core (or former) wrapped with transposed layers of superconducting tape.

Resistive laminates, like those soldered to each tape in typical FCL cables to prevent burnout [11, 17], may not be required in CORC® FCL wires due to the high level of current sharing enabled by the frequent overlapping of contacts between tapes throughout the conductor. To demonstrate the advantages and potential of operating CORC® conductors as FCL cables, short CORC® FCL wires of 3–4 mm thickness with critical currents (I_c) up to 1.1 kA were designed and manufactured, and their voltage versus current ($V(I)$) characteristics were measured under sudden overcurrents from 110% to 300% of I_c in liquid nitrogen.

When a superconducting cable has quenched due to a fault, the shunted current within the cable generates a significant amount of Joule heating in a short period of time. To prevent damage due to the temperature rise in the cable, careful design considerations are essential. To limit overcurrent in the required time and enable fast recovery, especially when cooled with low heat capacity coolants such as helium gas, it is desirable to incorporate an alternate route for the fault current to dissipate heat and/or bypass the protected equipment while the CORC® FCL conductor recovers. For this reason, the initial development of CORC® FCL wires was taken one step further by testing the viability of a CORC® FCL hybrid conductor, in which current is transferred automatically into a parallel normal path located outside of the superconducting FCL cable's cryogenic environment in the event of a fault.

2. Experimental

The building blocks of the CORC® conductor topology are the HTS tapes that are coaxially wound around a small former as seen in figure 1. To prevent excessive tensile strain on the

ReBCO layer due to bending, the tapes are wound facing the former. CORC® cables with diameter of 5–8 mm typically contain 20–50 4 mm wide tapes with 50 μm thick substrates, while CORC® wires are between 2.5 and 5 mm in diameter and are wound using HTS tapes of less than 3 mm width with 30 μm thick substrates. Tapes from different manufacturers vary widely in cross section and therefore vary also in mechanical and normal state electrical properties. Two 4 mm wide REBCO tapes with 7.5% Zr-doping manufactured by SuperPower Inc. containing 50 μm thick Hastelloy substrate with 1–3 μm thick silver cap layer and a 5 μm thick surround plated copper layer were tested in boiling liquid nitrogen to various applied currents. One tape had an additional 5 μm of PbSn solder plating, and a 50 μm CuNi tape laminated (soldered) onto the REBCO side of the tape. Two CORC® wires were designed using 2 mm wide REBCO tapes manufactured by SuperPower Inc. containing 30 μm thick Hastelloy substrates, also with 5 μm Cu plating [18]. The wire properties are summarized in table 1. Wire 1 utilized a C101 solid copper (Cu) former, while wire 2 was optimized for FCL application by using a high-resistivity 304 solid stainless steel (SS) former. Wire 2 was made using tapes from 5 different manufacturing batches with average I_c ranging from 48 to 69 A, representing a significant spread in I_c values. Each CORC® wire was insulated with 25 μm thick polyester heat shrink tubing and was 15–16 cm in length between the terminations.

The CORC® wires were terminated within 15 cm long copper tubes of 4.6 mm ID and 6.4 mm OD. The tapes were tapered to insure direct contact to the tubes and then the terminals were filled with indium solder. Voltage taps were located just inside the terminals on the side where the wire exits, approximately 15–16 cm apart. The resistance of the terminations measured between these voltage taps was approximately 16 nΩ for wire 1 and 46 nΩ for wire 2 at 76 K.

The I_c of CORC® wires was determined by curve-fitting the electric field (voltage across the terminations divided by the superconducting wire length) as a function of the current E(I) using the standard I_c equation [16] and the electric field criterion of 1 μV cm^{-1}. Overcurrent tests were performed in a bath of liquid nitrogen at 76 K in the DC overcurrent test facility at ACT by increasing the current within a single step from below I_c to between 150 and 350% I_c. The facility can deliver current pulse rates up to 1 MA s^{-1} and a maximum current of 13 700 A. The pulse rise-time in our current test setup was limited by the slew rate of the power supplies which is about 4 ms. While much of the data collected was averaged into 1 ms intervals, the data was taken at a rate of 50 kS s^{-1} with a voltage resolution of 60 nV.

CORC® wire 2 was chosen as the HTS leg of a hybrid FCL cable that includes a normal parallel current path at room temperature, but no switch to isolate the HTS leg following an overcurrent event. The experimental setup is shown in figure 2. A standard shunt ($R = 16.6\ \mu\Omega$) was used in the normal path to measure the current and the resistance of the normal conducting path (R_{nc}) was chosen so that it carried a small fraction of the total current (<9%) during typical operation below I_c while the superconducting path (including

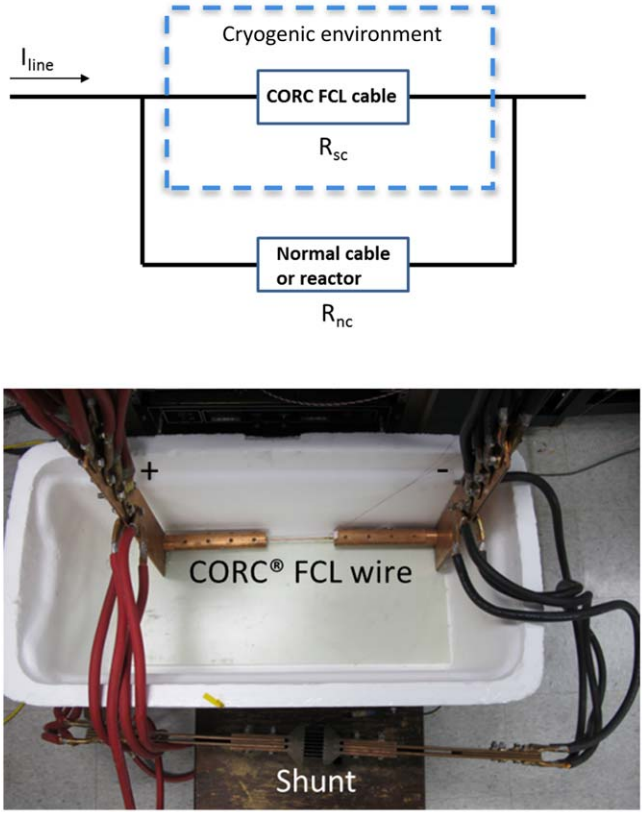

Figure 2. Above: a schematic of the hybrid CORC® FCL setup. Below: a picture of the laboratory test setup with the resistive shunt located outside of the cryogenic environment.

terminations) had a significantly lower resistance (R_{sc}) and carried most of the current. Overcurrent was then pulsed into the circuit to simulate a fault condition while the voltage was measured across the CORC® FCL wire and the shunt. Current flowing through the entire circuit was measured using a 4 kA rated transducer.

3. Results

3.1. Overcurrent testing of REBCO tapes and CORC® FCL wires

To allow a comparison to CORC® conductors, the E(I) response of individual REBCO tapes under overcurrent was measured in boiling liquid nitrogen at 76 K. Figures 3(a) and (b) show the applied current (as a percentage of the critical current) as a function of time for several tests on a REBCO tape with and without a bonded laminate, respectively. Figures 3(c) and (d) show the respective corresponding electric field as a function of applied overcurrent. Data are displayed at one ms interval. For some of the tests, the power supply in the test setup briefly overshoots the current resulting in the oscillations of applied current around the set value that can be seen in figures 3–5. Neither tape develops a significant (>10 V m^{-1}) amount of voltage within several (<30) ms unless the applied current is in excess of 140% I_c. At about 250% applied overcurrent, the bare REBCO tape's electric

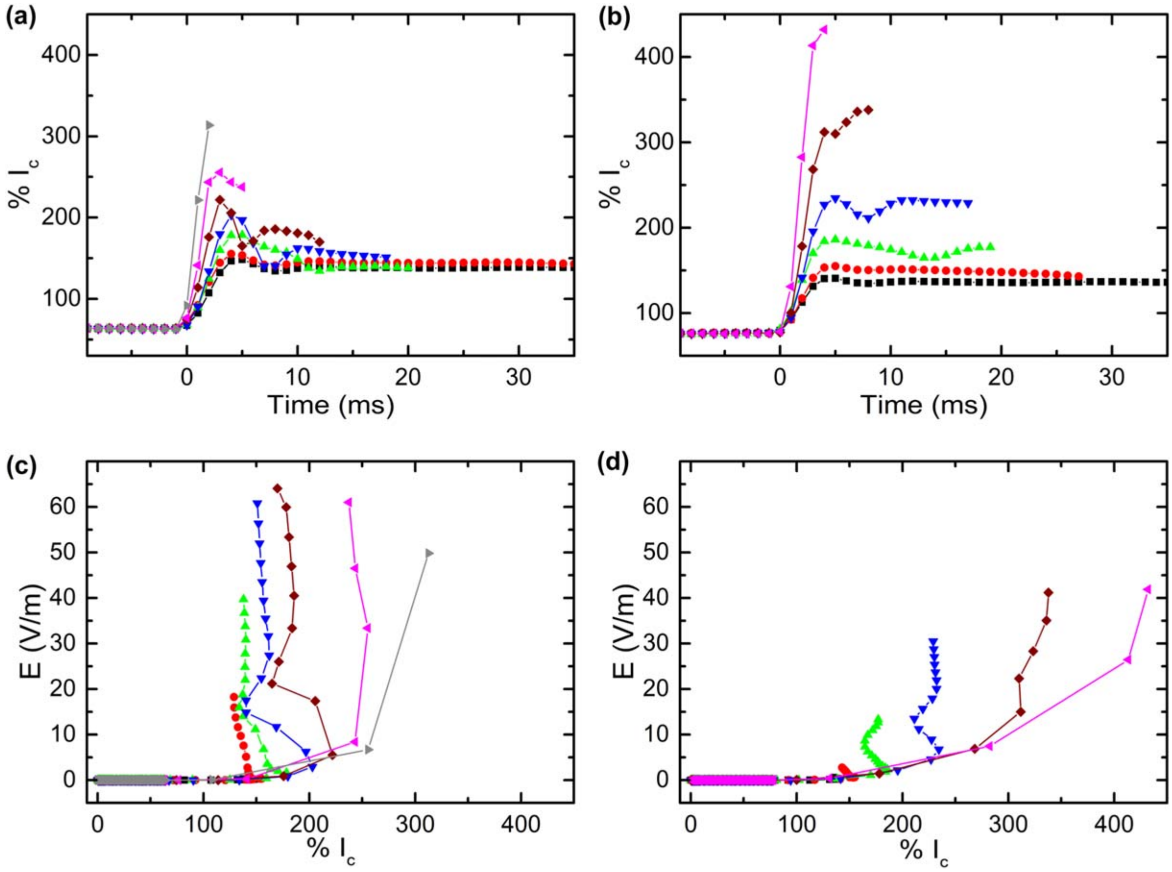

Figure 3. Applied overcurrent as a function of time for REBCO tapes (a) without and (b) with an added resistive laminate. Corresponding electric field as a function of applied overcurrent for REBCO tapes (c) without and (d) with an added resistive laminate. The different colors/symbols indicate different applied levels of overcurrents. Data taken at 76 K.

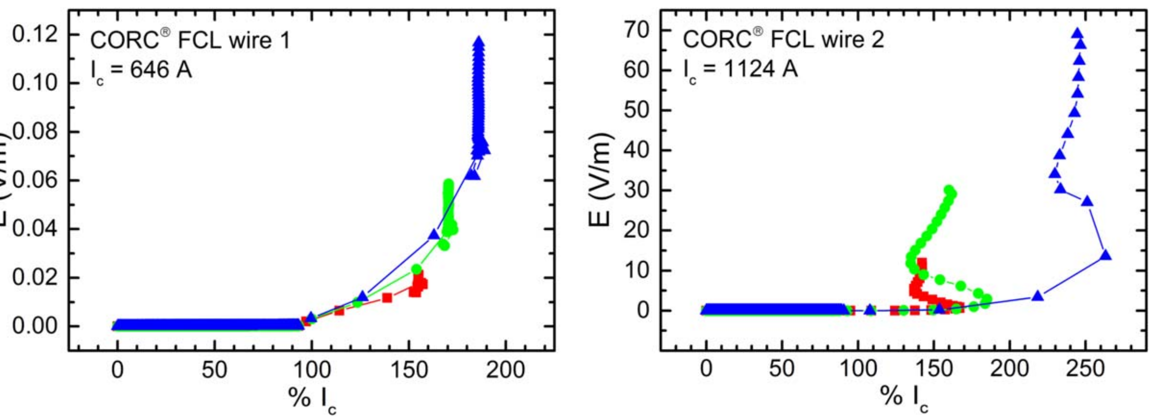

Figure 4. Electric field as a function of various applied overcurrents for CORC® FCL wire 1 (left) and wire 2 (right) at 76 K. The different colors/symbols indicate different applied levels of overcurrents.

Table 1. Properties of prototype CORC® FCL wires.

Sample name	Former material	Number of tapes	I_c at 76 K (A)	J_e at 76 K (A mm^{-2})	Wire diameter (mm)
CORC® wire 1	Cu	16	646	80	3.2
CORC® wire 2	SS	18	1124	99	3.8

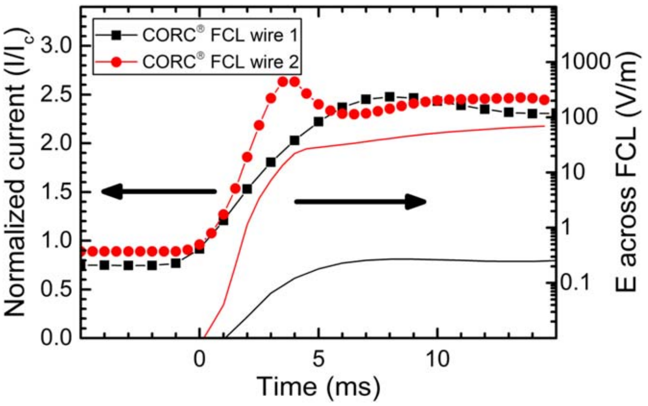

Figure 5. Applied overcurrent (I/I_c) as a function of time (symbols) and corresponding electric field (lines) for the two CORC® FCL wires tested up to about 250% of I_c at 76 K.

field increased to about 30 V m^{-1} within the 3–4 ms rise-time of applied current and then doubled to about 60 V m^{-1} within the next 3 ms. For the laminated tape, significantly higher applied overcurrent is required to reach similar values. For instance, 400% I_c has to be applied to the laminated tape to reach around 30 V m^{-1} in a similar timeframe. The laminate adds electrical stability to the REBCO tape which is important to protect the conductor from burnouts, but at the cost of increased response time at a given overcurrent.

To determine the E(I) response of the CORC® FCL wires under overcurrent as well as the impact of the former materials with significantly different resistances, pulsed overcurrent tests were performed on CORC® FCL wires in boiling liquid nitrogen at 76 K. Figure 4 shows the plots of electric field versus current as a percentage of the critical current of several tests. Figure 5 shows the voltage increase as a function of the current and time for both the wires when tested under similar overcurrents of about 250% I_c. The maximum current applied is 1600 A in wire 1 and 2960 A for wire 2. Within the 4 ms rise-time, CORC® wire 2 developed approximately 22 V m^{-1}, which is over 70 times higher than CORC® wire 1. The power dissipation for CORC® wire 2 is thus in excess of 65 kW m^{-1}, resulting in a rapid temperature increase of the wire, further increasing its voltage to about 70 V m^{-1} after another 10 ms at which point the power dissipation is about 190 kW m^{-1}. CORC® wire 1, which had a smaller outer diameter with the copper central former, developed significantly lower voltage despite having a maximum current density that was similar (200 A mm^{-2} compared to 260 A mm^{-2} in CORC® wire 2).

3.2. Overcurrent testing of a hybrid CORC® FCL conductor

CORC® wire 2 was tested as part of a hybrid cable according to the layout presented in figure 2 to test the application of the FCL wire as part of a more complex circuit. Current was driven into the circuit to evaluate the development of the voltage across the superconducting wire, diverting the current into the normal path as R_{sc} becomes significantly larger than R_{nc}. Figure 6 shows the current versus voltage response of the hybrid CORC® wire as a function of time across the FCL wire and across the shunt. Before the fault condition was simulated with an overcurrent pulse, 1117 A was run through the circuit representing normal operating conditions where FCL CORC® wire 2 carried 1020 A (91% I_c) and the normal resistive path carried 97 A. The peak FCL current of around 2600 A was measured during the current rise-time of 3.5 ms after increasing the overall current to 3600 A. After another 1.5 ms, 50% of the total current had diverted into the normal current path at room temperature as the voltage across the 15 cm long FCL cable approached 3 V, or 20 V m^{-1}. The voltage leveled off at around 15 V m^{-1} and the current in the FCL leg of the circuit decreased to around 1000 A, during a period of 10 ms at which the overcurrent was applied, while the normal path carried the other 2600 A. This is a very promising result that shows the feasibility of CORC® FCL hybrid cable concept. Longer length FCL wires will develop significantly higher voltages that would drive more current into the normal cable on an even faster timescale.

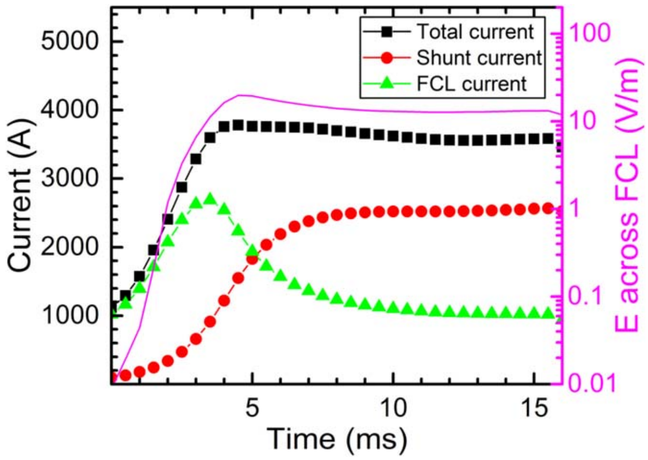

Figure 6. Current and electric field as a function of time in the hybrid CORC® FCL configuration of CORC® wire 2 after an overcurrent in excess of 300% I_c was applied at 76 K.

3.3. Cycling of the CORC® FCL wire to various overcurrents

CORC® wire 2, which was optimized for FCL operation, was tested extensively under various applied currents both as a stand-alone FCL and as part of the hybrid cable setup discussed in the previous sections. Figure 7 shows the applied peak overcurrents (I/I_c) as a function of test number. The CORC® wire likely heats to about room temperature within a timeframe of 3–5 ms during many of the overcurrent tests, after which it is cooled back to 76 K as soon as the current is switched off and the heating stops. The critical current of the wire was determined before and after the entire overcurrent test routine by measuring the electric field as a function of increasing current as the wire transitioned from the superconducting to normal state (figure 8). The overlapping lines show that the cable performance remained unchanged even after 89 overcurrent tests.

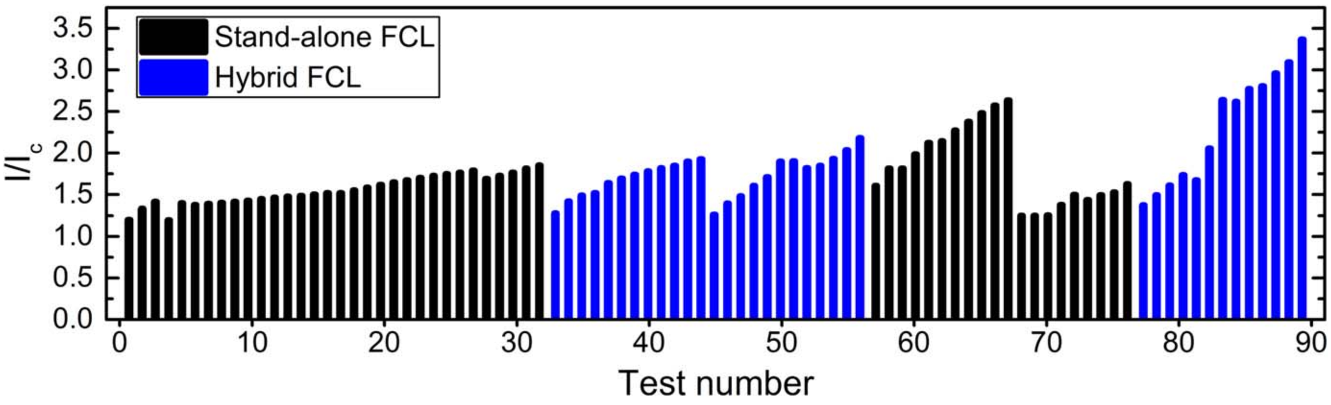

Figure 7. Overcurrent applied to wire 2 as a function of test number as a stand-alone FCL wire and as part of the hybrid FCL system at 76 K.

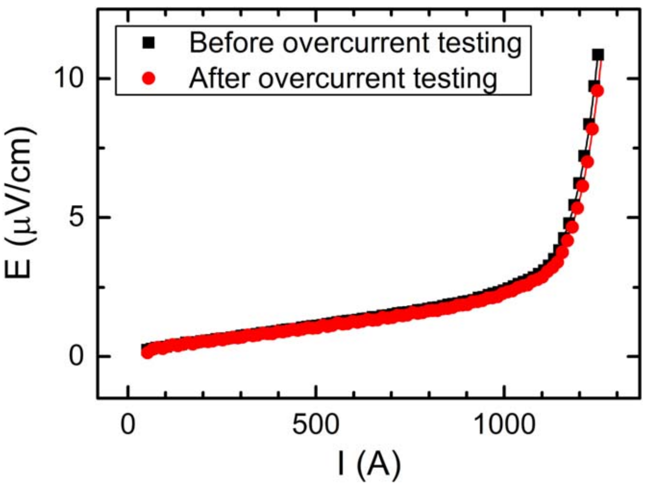

Figure 8. Electric field as a function of current at 76 K measured across the terminals of CORC® wire 2 before and after 89 fault current tests.

4. Discussion

CORC® wire 2 developed significant voltage upon application of currents in excess of I_c as seen in figures 4 and 5. At applied overcurrents of about 2.5 times I_c, wire 2 dissipated peak power of 190 kW m^{-1} and total energy of 1.4 kJ m^{-1} during the 15 ms test. While the wire used for these subscale tests had a small number of HTS tapes and a relatively low current rating of just over 1 kA compared to typical CORC® wires, scaled to an 8 kA rating, the voltage developed over CORC® FCL wire 2 would result in a load of 0.4 MW m^{-1} at 22 V m^{-1} or 1.4 MW m^{-1} at 70 V m^{-1}. This substantial amount of power can thus be dissipated to save sensitive equipment on a much quicker timescale than possible with DC circuit breakers on the market [2], [3]. While the fault currents can be limited nearly instantaneously, the associated temperature rise in the FCL cable must be mitigated by effective cooling, which is limited by heat transfer from the cable to the cryogen. A fast acting switch could be used after 4–8 ms to divert the overcurrent entirely to bypass protected equipment or through a reactor with sufficient resistance to limit the current while the resistive FCL wire recovers. No switch should be needed to isolate the superconducting wire while the reactor dissipates the overcurrent if the resistance of the CORC® FCL wire is sufficiently maximized in the overcurrent fault condition.

The ratio of the fault to operating current is a design consideration of CORC® FCL conductors to tailor their performance for use in a wide range of applications. This can be done on the tape level when designing the tape cross section, or on the cable level by changing the former material or adding non-superconducting tapes with relatively high electrical resistivity. The increased voltage for wire 2 with the stainless steel former verifies that the copper former used for CORC® wire 1 provided too much electrical stabilization for CORC® wire 1 to develop a significant voltage. Both wires appeared to have good thermal stabilization, as the quench appeared to initiate across the entire length of the wire (as observed by nitrogen boiling) and neither wire showed any I_c degradation following dozens of overcurrent tests. While the superconducting to normal transition is thought to initiate at the terminations due to their sensitivity to the self-field of the CORC® wire [16], the relatively low resistance (typically below 100 nΩ) of the terminations compared to that which develops over the CORC® wire during overcurrent tests suggests the quench is not confined to the terminations. Further testing is needed to quantify how the terminations may affect the quench propagation for longer cables or during slower faults.

The arrangement of HTS tapes within the CORC® FCL conductor is a significant advantage over other cable topologies for FCL use. Each layer of the conductor consists of 3–4 superconducting tapes, coaxially wound with a twist pitch between 5 and 20 mm, with every other layer transposed. This allows each tape to be in direct contact with every tape in the layers it is sandwiched between. If a defect exists in HTS tapes where a hotspot nucleates, there are up to six to eight alternate superconducting paths for the current and/or heat to flow, making the CORC® cable or wire rather robust in terms of electrical and thermal stability. In addition, adjusting the current rating or normal state resistance of the CORC® conductor is easily accomplished by selecting the number of superconducting and normal tapes. HTS tapes with significant spread in critical current were used to build the CORC® FCL wires discussed here. The survival of the wires with no degradation after extensive overcurrent testing indicates that current sharing keeps the hotspots that may occur in the lower I_c strands from causing damage to the conductor as a whole.

Most of the testing presented here was focused on the first ~15 ms of a fault because limiting a fault within this timeframe is difficult for mechanical switchgears, particularly for high current DC systems. Testing of the hybrid CORC wire summarized in figure 6 revealed a significant result where even in the absence of a switch, a significant portion of the fault current can be diverted to a parallel resistive path outside of the cryogenic environment. This minimizes the heat load on the cryogenic environment and is particularly important in applications where cooling power is limited, as is the case for He-gas cooled power transmission cables. For example, the energy dissipated during the 15 ms long test shown in figure 6 across the superconducting portion of the circuit was about 260 J m^{-1}. The cooling capacity of a system would only need to be 10 W m^{-1} to keep the recovery time to less than 30 s. Diverting most of the current to a parallel path also reduces the rating needed for a mechanical switch to eventually disconnect the superconducting leg of the circuit, while also allowing an option to use the diverted current to keep certain systems online that are rated to tolerate such faults.

5. Conclusion

Substantial progress has been made in the development of CORC® power transmission or distribution cables and wires with a valuable new technology feature of inherent fault current limiting (FCL) capability. CORC® FCL wires with critical currents up to 1.1 kA were designed, manufactured, and tested. It was found that a high-resistivity former is crucial to develop significant voltage across the CORC® wire, in excess of 20 V m^{-1}. In addition, the CORC® FCL wires were shown to be insensitive to I_c variation in individual tapes due to the high level of current sharing made possible by the CORC® wire topology. This represents a key advantage of the CORC® technology, besides the very high current density and flexibility of CORC® FCL cables and wires.

By providing a parallel normal path to the FCL conductor located outside of the FCL conductor's cryogenic environment, it was shown that the hybrid CORC® FCL conductor concept is feasible. Sufficient voltage developed under applied overcurrent to effectively limit the fault current in the CORC® FCL wire and transfer most of the current into the normal path within the rise-time of an overcurrent pulse of about 5 ms. Since this test was performed on an extremely short conductor, we conclude that longer FCL wires will develop considerably higher voltages that will exhibit even better performance, potentially allowing for much slower circuit-breaking switch times or even eliminating the need for a switch.

Based on the results on the test cables, we are confident that the CORC® FCL concept is viable and offers key advantages over other high-temperature superconducting FCL cable concepts. Specifically, we demonstrated electric field values in a CORC® FCL wire in excess of 20 V m^{-1} after a current rise-time of 3–4 ms up to 2.5 times I_c. The peak power output when testing was up to 190 kW m^{-1} with an energy dissipation of up to 1.4 kJ m^{-1} during the 15 ms tests. For a CORC® FCL wire scaled to 10 meters with an 8 kA rating, this would result in a load of 4 MW, which can be dissipated to save sensitive equipment on a much quicker timescale than any DC circuit breaker on the market. Furthermore, CORC® FCL wire design can be tailored to limit different levels of overcurrent and recovery time, allowing applications in many different power distribution systems.

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