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Development of CORC® cables for helium gas cooled power transmission and fault current limiting applications

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Abstract

High-temperature superconducting (HTS) direct current (dc) power cables allow high levels of power transmission and distribution at low loss and can be tailored to effectively limit fault currents. HTS Conductor on Round Core (CORC®) power transmission cables offer additional benefits over other HTS cable designs, including a much higher current density and a higher degree of flexibility. These benefits make CORC® cables most suitable for applications in confined spaces where tight bends are required, such as onboard naval ships and in data centers. The development of CORC® power transmission cables for operation in pressurized helium gas is described, including their ability to act as fault current limiting cables. The 10 m long bipolar dc CORC® power transmission cable system is designed to operate at a current of 4000 A per pole at 50 K in pressurized helium gas. The test results at temperatures between 60 K–74 K in helium gas at a pressure of 1.7 MPa are described both during normal operation and during an overcurrent event. The results demonstrate the potential of CORC® cables to operate at currents exceeding 10 000 A per pole at 50 K at current densities of more than 200 A mm^{-2}, resulting in the most energy dense superconducting power transmission cable to date. The successful operation during an overcurrent event also shows the added benefits of the high level of current sharing between tapes in CORC® cables that allow them to be operated as FCL cables without the need to incorporate a substantial amount of stabilizer. The successful test is a major milestone towards reliable high energy density power transmission in helium gas cooled superconducting power systems based on CORC® cables.

Keywords: CORC® cable, superconducting power cable, helium gas cooling

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

1. Introduction

High-temperature superconducting power cables have been developed over the past two decades as a more efficient alternative to copper or aluminum power transmission cables. Long length production of high-quality $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes and RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) coated conductors have resulted in successful demonstration projects and actual applications of liquid nitrogen cooled HTS ac cables in the electric power grid [1–5]. The widespread replacement of conventional power cables by HTS cables has yet to materialize because of the high cost of HTS cables and the associated cryogenic systems as well as the perceived risks of the new technology involving cryogenics by electric power utilities. HTS power cables are

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considered primarily for applications where the required higher power capacity cannot be met with conventional cables, or where the additional benefits of HTS, such as fault current limiting capabilities [6], are invaluable.

The size, weight and relatively high loss of conventional power transmission cables present a substantial challenge for applications where ever-increasing power densities are required in confined spaces, such as onboard naval ships, data centers and electric aircrafts. Restrictions on operating voltages in these applications, such as 12 kV in future electric naval ships, require power transmission at high currents for which HTS power cables present a viable solution.

Superconducting power cables that were designed for use in the electric power grid contain superconducting tapes wound into a limited number of layers onto a large former. Tri-axial HTS cables developed by ULTERA [1], rated at 3 kA at 77 K, contain a hollow former of about 36 mm in diameter. SuperPower successfully demonstrated a design in which three individual cables formed a 3-phase ac power cable [2]. Each phase had a critical current (I_c) of about 2800 A at 77 K and contained a 16 mm diameter stranded copper former. The relatively large size of these cables limits their minimum-bending diameter to several meters, making them impractical for use in most confined spaces.

Helium gas cooled operation of HTS cables reduces the asphyxiation hazard present when the cables are used in confined spaces, compared to operation in liquid nitrogen. In addition, operating temperatures below those available with liquid nitrogen (no lower than 63 K), at which the performance of the superconducting tapes is significantly higher, are readily achievable using helium gas. Helium gas cooling allows for cables to be designed with higher current densities or a lower number of tapes, thereby reducing the cost of the cable. The US Navy has particular interest in developing dc HTS power cables that operate at currents exceeding 3000 A per pole, while being cooled with pressurized helium gas to temperatures between 30 K–65 K. A 30 m long monopole HTS cable was successfully demonstrated at the Center for Advanced Power Systems (CAPS) in helium gas at a temperature of 65 K, where the cable carried 3000 A [7]. The cable followed the design of earlier, less compact HTS demonstration cables [1], limiting the operating current density and restricting its allowable bending diameter.

CORC® cables that are being developed by Advanced Conductor Technologies LLC are compact and flexible making them suitable for magnets [8–10] and power transmission applications [11, 12]. CORC® cables contain thin formers of less than 6 mm in diameter onto which up to 50 REBCO tapes are wound, resulting in a cable diameter of less than 8 mm. Compared to other HTS cable designs, the relatively smaller diameter and shorter twist pitch at which the tapes are wound in CORC® cables results in allowable cable bending radii of less than 100 mm without a significant degradation to the superconducting properties.

Helium gas cooled CORC® dc power transmission cables are being developed with focus on high power density, cable production at long lengths, and the development of practical cable terminations and feeders to enable efficient, low loss current injection from conventional power system components at room temperature into the superconducting cable at cryogenic temperature. We present the development and a successful demonstration of the first helium gas cooled two-pole CORC® dc power transmission cable system rated at an operating current of 4000 A per pole at 50 K. The successful demonstration of the cable system in helium gas during normal operation and during an overcurrent event, at which the cable was operated as FCL cable, will be outlined.

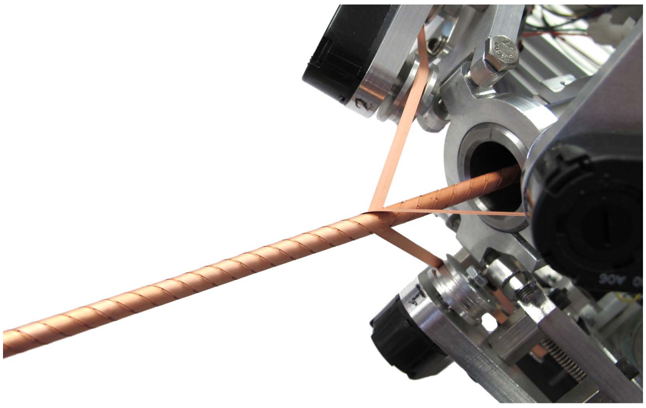

Figure 1. Winding head of the custom CORC® cable machine containing three tape spool holders.

Figure 2. CORC® cable of 7 mm diameter containing 30 tapes.

2. Experimental

2.1. CORC® power transmission cables

The CORC® power transmission cables outlined in this paper were wound with a machine capable of winding CORC® cables in excess of 50 m in length. The CORC® cable machine consists of a single winding head onto which up to four spool holders could be mounted (figure 1). The tapes were wound with high accuracy in terms of winding tension and position, resulting in tape-to-tape spacing that varies by less than 0.2 mm. CORC® cables typically contain up to 50 tapes wound into as many as 20 layers (see figure 2).

The CORC® cables that were part of this program contained 24 tapes that were wound in eight layers onto a former of diameter between 5–5.5 mm. Winding the REBCO tapes

Table 1. CORC® power cables fabricated and studied.

	CORC®-1	CORC®-2	CORC®-3
Type	Single-strand	Single-strand	Twisted pair
Former size	5.0 mm	5.5 mm	5.3 mm
Former material	Cu	Cu	Al
Tapes per cable	6	24	24
Cable diameter	5.8 mm	6.6 mm	7.0 mm
I_c (77 K) @ 100%	600 A	2830 A	3000 A
Expected I_c (60 K)	2040 A	9622 A	10 200 A
Cable length	0.8 m	1 m	10 m
Cryogen	LN_2 + GHe	LN_2 + GHe	GHe

with the REBCO layer on the inside of the wind, putting them under axial compression, allows for much higher winding strains without any irreversible degradation occurring, compared to winding the tapes with the layer on the outside [10]. The combination of the relatively small size of CORC® cables and the short twist pitch of less than 30 mm at which the tapes were wound onto the former results in a highly flexible conductor. CORC® cables can be bent to radii of less than 100 mm, depending on their layout, making them ideal for power transmission applications in confined spaces that include tight bends. The high number of tape layers and short twist pitches also result in a relatively high level of current sharing among the tapes in the CORC® cable, making them less prone to burnout in the presence of tape defects, even when subjected to overcurrent.

A total of three CORC® cables were prepared for this study (see table 1). Cable CORC®-1 contained six REBCO tapes and was prepared to measure the temperature dependence of I_c in both liquid nitrogen (LN_2) and helium gas (GHe). Cable CORC®-2 contained 24 REBCO tapes, resulting in an I_c at 77 K of about 3000 A at 100% performance retention. Cable CORC®-3 was a 10 m long two-pole dc power cable that was formed by twisting two CORC® cables, each containing 24 tapes, together.

The CORC® cables were wound from REBCO tapes from SuperPower Inc., which had a 50 μm thick substrate, were 4 mm in width, and were surround plated with 5 or 20 μm thick copper. The formers in the CORC® cables were made from solid copper or solid aluminum. Each cable was insulated with a layer of 50 μm thick polyester heat shrink tubing. The terminations of the cables were fabricated using copper tubes with 12.6 mm in diameter. The layers of REBCO tapes in the terminals were tapered, allowing direct contact between each tape in the cable and the copper tube. The terminations were filled with Sn63Pb37 solder [13, 14]. The former was also embedded into the solder of the terminations and was in direct contact with the tapes in the inner layer, allowing for current sharing between the tapes and the former.

The two CORC® cables from which the two-pole power transmission cable was prepared (CORC®-3) were wound separately and each had a length of about 11 m. The longer length allowed sufficient length for the terminations to be mounted and for the cables to extend far enough beyond the 10 m long Nexans cryostat with 39 mm inner diameter (type 39/66) to connect them to the feeder cables. Figure 3(a) shows one of the 11 m long CORC® cables, while figure 3(b) shows a close-up of the cable after a single layer of heat shrink tube insulation was applied. A layer of tin-plated copper braid was added on the outside of each cable (figure 3(c)) to protect them from damage during installation into the cryostat. Another layer of heat shrink tubing was applied onto the copper braids to keep them in place during cable installation.

2.2. Cable installation and instrumentation

Two types of cryostats were used for testing the CORC® power transmission cables in pressurized helium gas. Cables CORC®-1 and CORC®-2, which were each about 1 m in length, were tested in a 1.5 m long rigid helium gas cryostat at CAPS. Current was injected from room temperature using copper bus bars that were connected to feeder cables entering into the helium gas cryostat through two side flanges. Each connection between the copper bus bar and the feeder cables was cooled in a bath of liquid nitrogen to reduce the conductive heat load from room temperature through the copper bus bars and feeder cables into the helium gas environment (figure 4).

Figure 5 shows the short helium gas cryostat at CAPS during testing of cable CORC®-1. The helium cryostat contained a liquid nitrogen jacket and two liquid nitrogen reservoirs to pre-cool the copper bus bars. The helium gas was injected into the helium gas cryostat using vacuum-insulated lines that ran through the liquid nitrogen bath. The helium lines were part of the flanges holding the current feeders. Helium gas was injected between the flange and the connection between the CORC® power and feeder cables. The feeder cables connecting the copper bus bars at 77 K to the power transmission cable located in the pressurized helium gas cryostat were copper braided cables during the test of cable CORC®-1. The resistive heating in the copper feeder cables limited the current of the test to about 2000 A. The copper feeders were replaced by more efficient feeder cables during the test of cable CORC®-2, allowing injection of the maximum current available from the power supply of 6000 A.

Figure 6 shows a schematic of the test configuration of the two-pole dc CORC® power transmission cable in which each pole was formed by a single CORC® cable. The cryostat was a 10 m long flexible cryostat in which the two-pole CORC® cable was inserted after both poles where twisted together at a pitch of about 0.2 m (figure 7). The power cable contained a single termination on each pole when inserted into the cryostat, which allowed for cutting the cable to the correct length after which the second pair of terminations was mounted. Custom cryostat end caps were connected to the flexible cryostat to allow easy access to the connection between the power cable and the feeder cables (figure 8). The copper bus bars were connected to the ends of the feeder cables and the connection was cooled with liquid nitrogen. Helium gas was injected or extracted from the ends of the cryostats, which also contained the interface for the instrumentation wiring.

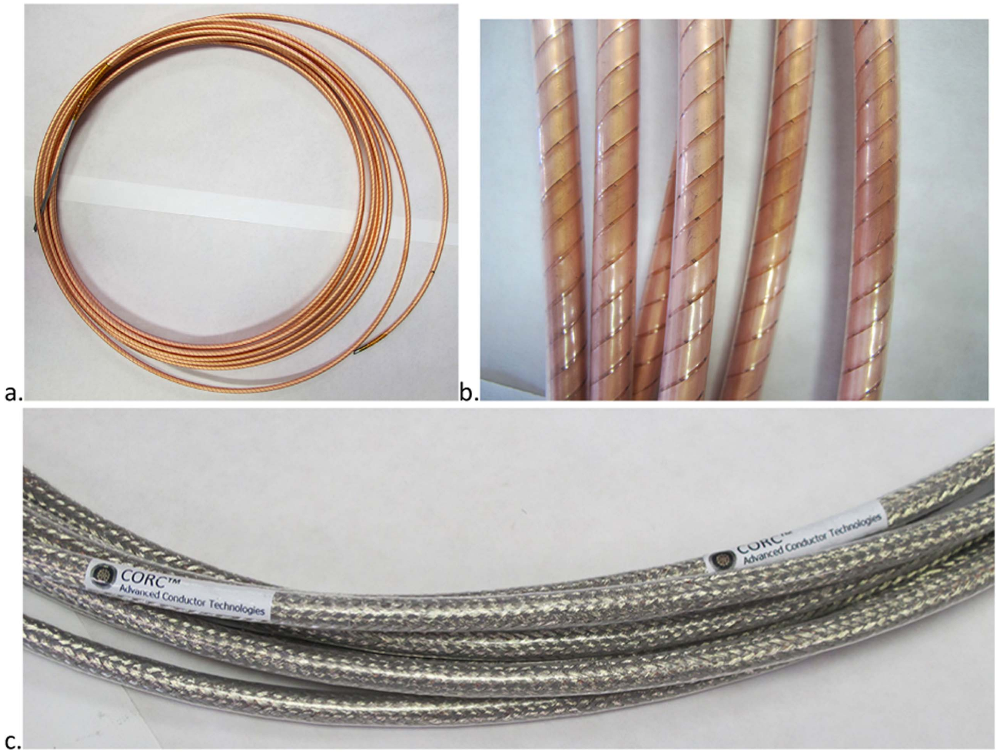

Figure 3. (a) One pole of CORC®-3 cable. (b) Detail showing the uniform gap spacing between adjacent tapes in the CORC® cable. (c) Copper braid applied to the outside of the cable.

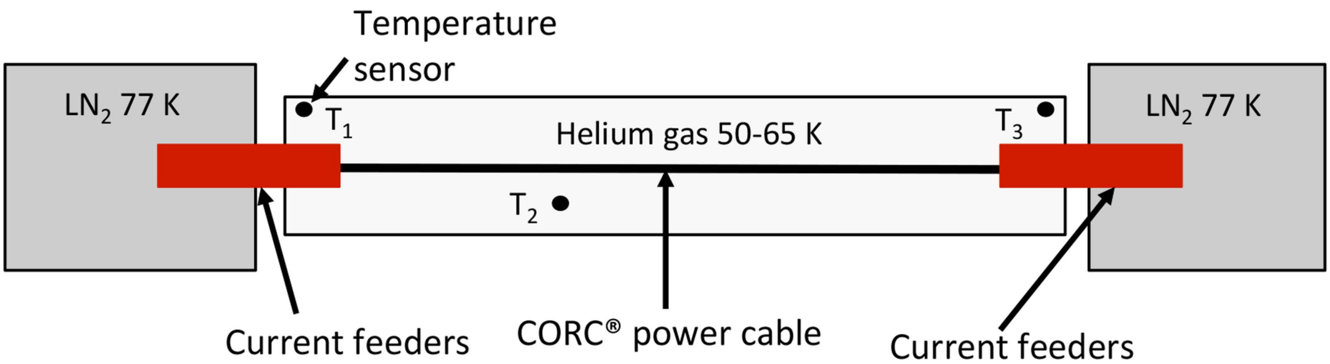

Figure 4. A schematic of the test configuration of the single-pole CORC® cables in helium gas.

The pressurized helium gas circulation system at CAPS consisted of a SPC-1 cryogenerator from Sterling Cryogenics, capable of providing helium gas flow rates of up to 10 g s^{-1} at a temperature as low as 50 K [15]. The maximum operating pressure of the power cable was 2.1 MPa (300 psi), while the minimum temperature of the power cable was determined by the heat load into the helium gas. The heat load of the flexible helium cryostat was about 1 W m^{-1}. The majority of the heat load into the system occurred through conduction along the feeder cables and through the flanges of the cryostat into which the feeders were mounted. This conductive heat load in combination with the limited cooling power of the cryogenerator limited the minimum temperature of the 10 m long two-pole power cable to about 60 K.

The cryostats in all three tests contained a number of temperature sensors to measure the temperature of the helium gas at different locations and the connection between the CORC® cables and the feeder cables (see figures 4 and 6). Voltages were measured over each power cable where the voltage contacts were embedded into the cable terminals. This allowed determination of the contact resistance of the cable terminals. The voltage was also measured over the connections between the power cable and the feeder cables.

3. Results

3.1. Temperature dependence of the CORC® cable critical current

One of the benefits of operating HTS power cables in helium gas is that the operating temperature can easily be reduced to

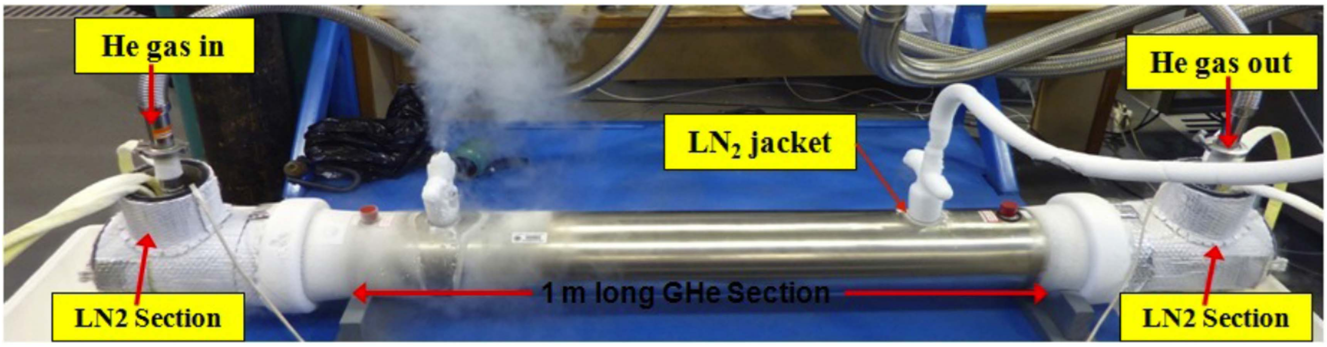

Figure 5. The 1.5 m long helium gas cryostat at CAPS with liquid nitrogen baths installed at either end.

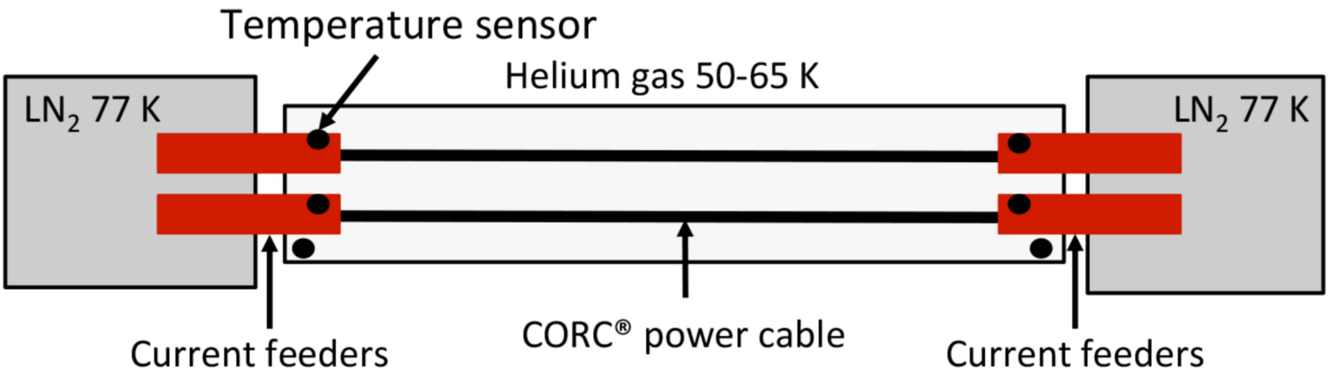

Figure 6. A schematic of the test configuration of the two-pole CORC® cables in helium gas.

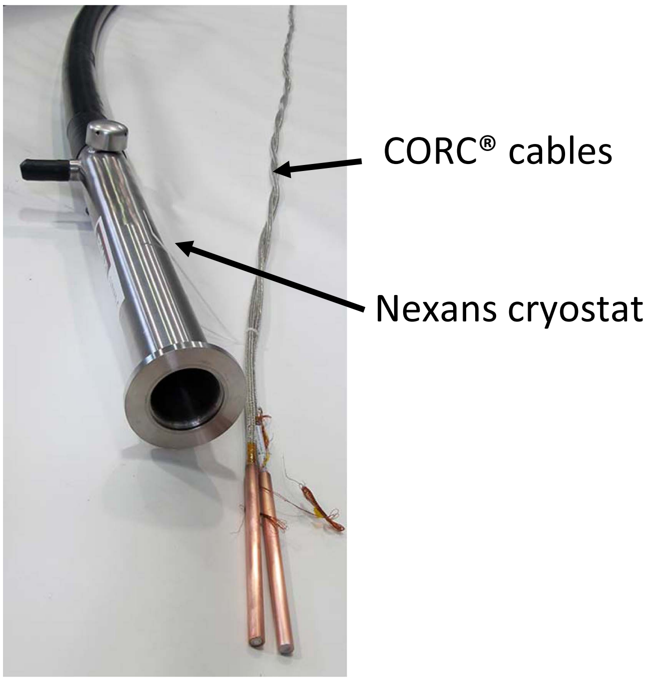

Figure 7. Overview of the 10 m long flexible cryostat and the CORC® dc power cable (CORC®-3) consisting of two twisted CORC® cables.

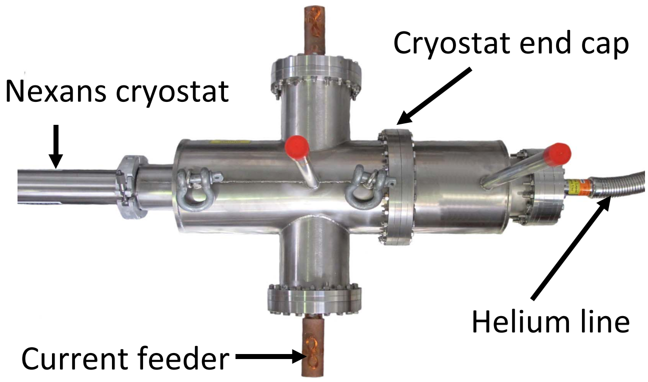

Figure 8. Custom cryostat connected to one end of the flexible cryostat. The copper ends of the two feeder cables that would be connected to the copper bus bar extend outward.

below the 65 K–77 K range limited by liquid nitrogen because nitrogen freezes at 63 K. The temperature dependent I_c results in a much higher operating current at lower temperatures, such as 50 K–60 K, accessible with pressurized helium gas. The first experiment outlined in this paper was performed to determine the temperature dependence of I_c of CORC® cables. The experiment was performed on cable CORC®-1 in the short helium gas cryostat at CAPS (figure 5) and was limited to a maximum operating current of 2000 A.

The temperature dependence of I_c was first measured in sub-cooled liquid nitrogen by pumping on the nitrogen bath to reduce the boiling temperature from 77 K down to 67 K. The temperature dependence of I_c was then measured in the same cryostat in pressurized helium gas between 62 K–74 K, as

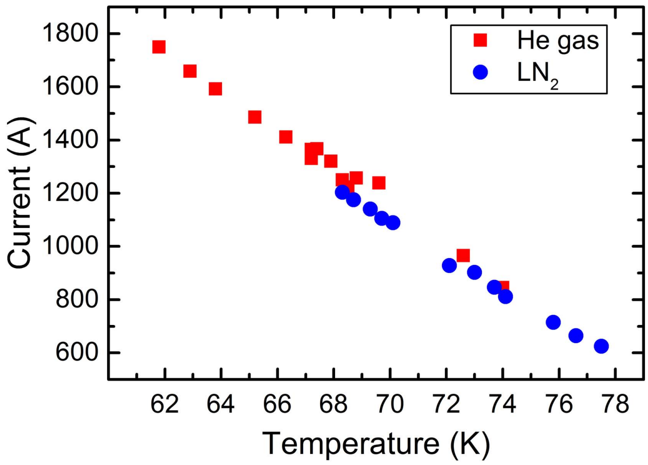

Figure 9. Temperature dependence of I_c of cable CORC®-1 measured in both sub-cooled liquid nitrogen and pressurized helium gas.

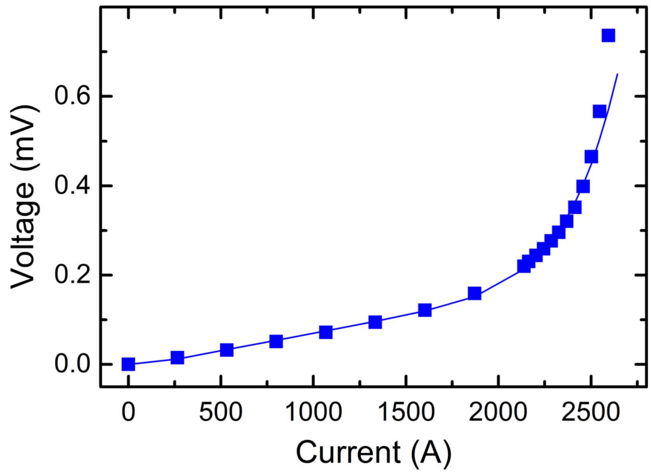

Figure 10. *VI*-characteristic of cable CORC®-2 measured at 76 K. The solid line is a fit to the data according to equation (1).

shown in figure 9. The I_c values measured between 67 K–74 K in liquid nitrogen corresponded to those measured in helium gas over the same temperature range. The critical current of cable CORC®-1 increased linearly with a reduction in temperature from about 600 A at 77 K to about 1800 A at 62 K. Heating in the copper feeders prevented further measurements below 62 K. At 50 K, the extrapolated cable I_c would thus be about 2600 A, or a factor of 4.4 times the I_c at 77 K, assuming the linear temperature dependence of I_c is not affected by the higher self-field of the cable. The effect of self-field on I_c in CORC® cables is expected to be much smaller than in single tapes. The self-field in CORC® cables is oriented mainly within the plane of the tapes wound into a helical configuration, compared to the self-field of a single tape that has a significant component perpendicular to the tape surface.

3.2. High-current CORC® cable test in helium gas

A 24-tape CORC® cable (CORC®-2) of about 1 m in length was manufactured in preparation for testing at CAPS in helium gas after the feeder cables in the cryostat were upgraded. The CORC® cable was tested in liquid nitrogen at 76 K, where the voltage was measured over the cable terminals, before it was shipped to CAPS. Figure 10 shows the voltage versus current (*VI*) characteristic, together with a fit to the data that includes the contact resistance of the two terminations, using equation (1):

$$V = IR + V_c\left(\frac{I}{I_c}\right)^n + V_0. \tag{1}$$

Here, V_c is the voltage at which the critical current was defined, which is 1×10^{-4} V m^{-1} times the distance between voltage contacts, R is the contact resistance of the terminations, V_0 is the inductive voltage offset and n represents the steepness of the superconducting transition. The critical current was 2287 A, or about 70% of the sum of the critical currents of all tapes in the cable. The lower value is not an indication of damage to the tapes in the cable, but is likely the result of a slightly higher temperature caused by heating within the terminals and by the larger effect of self-field when the tapes expand within the terminals, resulting in widening of the gaps between them. The terminal-to-terminal resistance was 77.8 nΩ.

The CORC® cable was inserted into the helium gas cryostat at CAPS, and the cable terminations were connected to the feeders using copper connectors. One of the connecters between the CORC® cable and one of the feeder cables was prepared before the cable was inserted into the short helium cryostat. The connection at the other cable end could only be completed after the CORC® cable was inserted into the cryostat. The very limited access to the connection resulted in the connector closed at insufficient contact pressure, forming a relatively high contact resistance. Figure 11 shows the voltage measured over the connectors when operated at 60 K up to the maximum power supply current of 6000 A. The connector on the inlet side, which was closed correctly, had a contact resistance of 130 nΩ at 60 K, while the connector on the outlet side had a resistance of 1.5 $\mu\Omega$. The heat generated in the connector at the inlet side at a current of 6000 A was only 4.7 W, while that in the connector at the helium gas outlet side was 52.5 W.

The cable was operated for over 2.5 h at a helium gas flow rate of about 8 g s^{-1}, during which time the current was increased stepwise to a maximum current of about 3400 A. The temperature of the helium gas at the inlet of the cryostat was between 60 and 61 K (figure 12), measured using temperature sensor T1 (see figure 4). The temperature measured halfway down the cryostat (sensor T2) was very close to the temperature of the helium gas at the inlet, even at high current. On the other hand, the temperature of the helium gas after it passed over the connector at the outlet side of the cryostat, measured with temperature sensor T3, increased

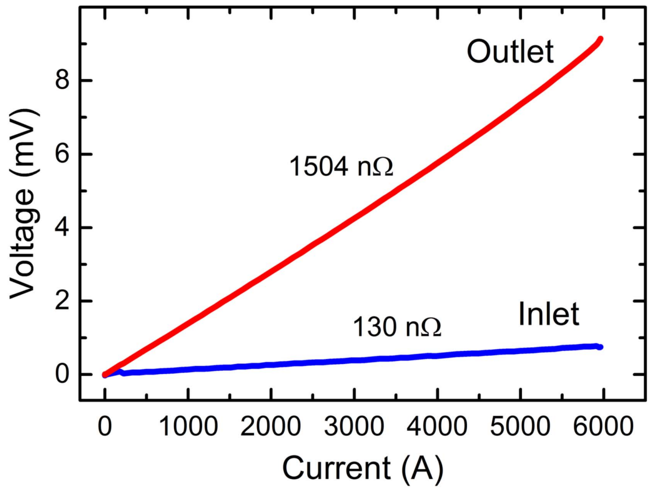

Figure 11. *VI*-characteristic of the copper connectors between the CORC® cable terminals and the feeders cables when operated in helium gas at 60 K for both connectors.

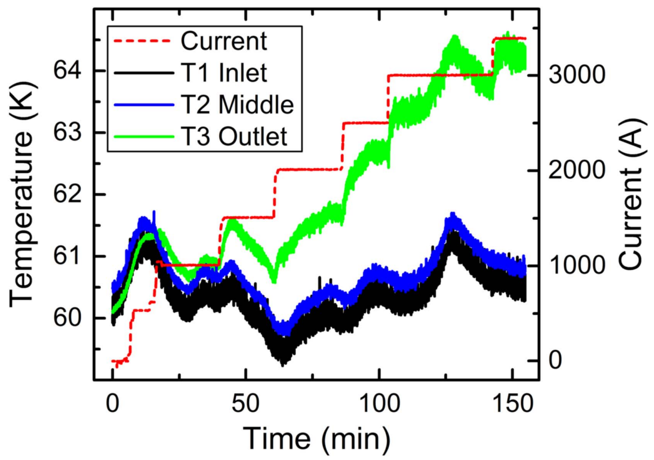

Figure 12. Temperature as a function of time at different operating currents of cable CORC®-2 in the short helium gas cryostat. The current was increased stepwise, while it was held constant for about 15–20 min between steps.

significantly with time after the current in the cable exceeded about 1500–2000 A. The heating in the connector limited the steady operation at currents in excess of 3500 A for an extended period of time. At higher currents, the temperature of the helium gas at the outlet had increased to 64 K compared to a temperature fluctuation at the inlet of about 2 K over the course of the test. Although the helium gas has only limited cooling power, it was still able to effectively cool the connector in which dissipation of approximately 52 W occurred.

The experiment was repeated at a constant current ramp rate of about 300 A s^{-1} to the maximum current available of 6000 A. Figure 13 shows the temperature as a function of time before and during the application of current. The temperature of the helium gas at the outlet of the cryostat increased noticeably after about 20 s when the current exceeded about 2000 A. The temperature increased more rapidly once the current approached the maximum value of

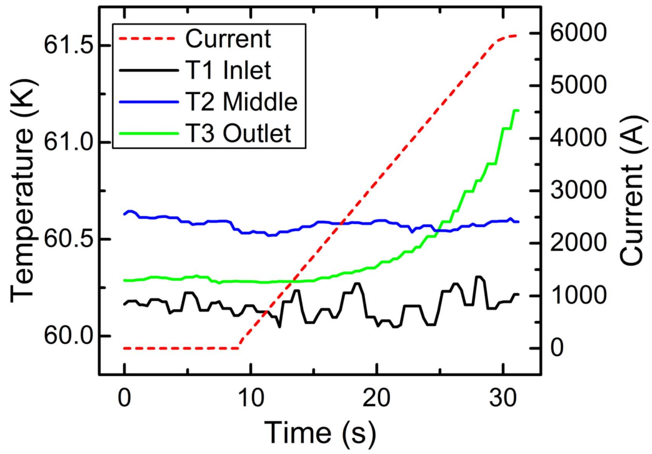

Figure 13. Temperature as a function of time at different operating currents of cable CORC®-2 in the short helium gas cryostat. The current was increased at a constant rate of about 300 A s^{-1}.

6000 A. The temperature of the helium gas in the middle of the cryostat, after it passed over the connector on the inlet side, did not show any significant increase, even at high currents. The results thus show that CORC® cables can be operated successfully in helium gas at very high currents, as long as local heating in resistive components such as connectors is kept to an acceptable level.

3.3. Test of a two-pole dc CORC® power transmission cable system in helium gas

The 10 m long two-pole CORC® power transmission cable (CORC®-3) was fabricated after the successful tests of the shorter monopole CORC® cable (CORC®-2) at 6000 A in helium gas. A second set of feeder cables was prepared and the cryogenic interface between the 10 m long Nexans cryostat and the two sets of feeder cables were manufactured, as outlined in section 2.2 (figure 8). The termination cryostats contained a 10″ Conflat flange that allowed easy installation of the CORC® cables and connections to both sets of feeder cables ensuring the connection between the feeder cables and the CORC® cables could be closed correctly.

The two-pole CORC® cable was cooled with helium gas at a pressure of 1.7 MPa (250 psi) and a mass flow rate of about 8 g s^{-1}. Each pole of the power cable was energized individually to determine I_c by increasing the current at a constant rate of 200 A s^{-1}, without the presence of the self-field of the second pole. Figure 14 shows the *VI*-curves of the two poles of cable CORC®-3 at a maximum temperature of 72 K measured on the connector at the outlet side of the cryostat. The I_c of pole 1 (Cable 1) was 4600 A, while that of pole 2 (Cable 2) was 4775 A. The current was increased past I_c until the cables quenched, while being protected using a quench detector that shut off the power to the cable when the overall voltage exceeded 3 mV. The current was ramped to the quench current several times to ensure the cables did not degrade due to the quenches. The cable was then operated as a two-pole dc power cable by connecting the terminals of the feeder cables on the outlet side of the cryostat in series.

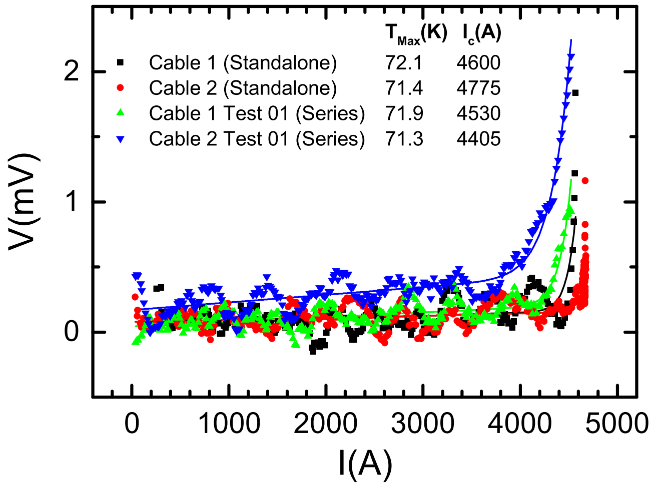

Figure 14. *VI*-curves of the two poles of cable CORC®-3 at a maximum temperature of about 72 K measured on the connector at the outlet side of the cryostat. The poles were energized separately when standalone and together when connected in series. Lines are fits used to determine I_c using equation (1).

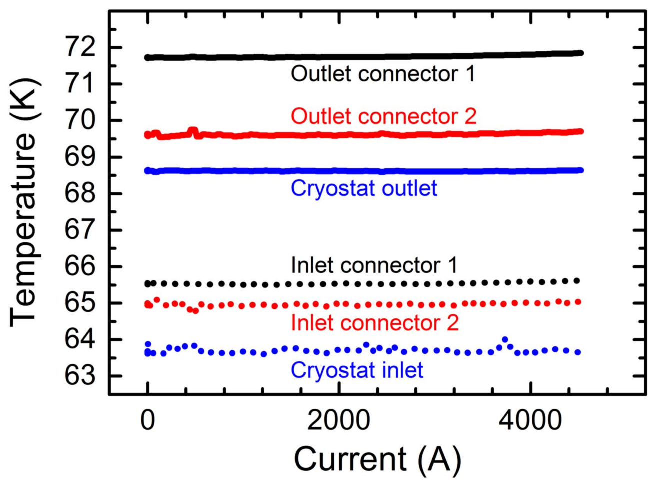

Figure 15. Temperature as a function of current during the two-pole operation of cable CORC®-3.

Current was increased at a rate of about 200 A s^{-1} until the cables quenched at a current of about 4600 A (figure 14). The critical current of both poles was reduced slightly to 4530 A for pole 1 and 4405 A for pole 2 due to the higher self-field of about 250 mT on the cables when operated in series.

The temperatures of the two pairs of connectors and the helium gas at the inlet and outlet of the cryostat are shown in figure 15 when current was injected during the two-pole operation mode of the cable. No significant increase in temperature was measured during the cable operation, even at the highest current of over 4500 A. The temperature of the helium gas at the inlet of the cryostat was 63.5 K, while it was 68.5 K at the outlet of the cryostat. The temperature of the connectors to the power cable at the inlet side of the cryostat was about 1.5 K–2 K higher than the helium gas at that location, which is likely due to the thermal conduction through the feeder cables and resistive heating in the connector. The temperature of the connectors to the power cable at the outlet side was about 1 K–3 K higher than the helium gas.

The voltage was measured over the entire cable, including the cable terminations, but no additional voltage contacts were present on individual cable sections. The quench of each CORC® cable in the two-pole cable likely originated at the location where the temperature was highest, and thus likely started in the cable terminations at the outlet side. The expected I_c of both poles at 77 K and 100% I_c retention was 3000 A. The temperature dependence of I_c as reported in section 3.1 suggests that at 72 K, I_c would be about 4500 A. The slightly higher I_c that was measured on the individual poles suggests that the cable terminations were at a slightly lower temperature, around 1 K lower than was measured on top of the connectors.

The temperature dependence of I_c suggests that the two-pole power cable would have an I_c of about 12–14 kA at 50 K, which would allow an operating current of 10 kA while operating at 80% of I_c. Operation at 10 kA at 50 K would also allow for a temperature margin of about 7 K. Operating at this temperature and much higher current would require a higher cooling power of the helium gas circulation system than is presently available at CAPS.

Cable CORC®-3 was tested as a fault current limiting cable by continuing the current ramp beyond the quench current while being cooled with flowing helium gas. The overcurrent had a maximum value of 6000 A, or about 133% of I_c at 72 K. The power supply had a maximum output voltage of 10 V. Cable CORC®-3 did not contain additional stabilizing material, such as laminates, besides the 20 μm thick layer of copper plating. The high level of current sharing between tapes in CORC® cables allowed current to easily bypass tape defects to prevent burnout, removing the requirement for additional stabilizing material which is typical requirement for FCL cables [16].

Figure 16 shows the current and voltage measured as a function of time over the two-pole power cable during the overcurrent event, with both poles connected in series. The current of the power supply was increased to 6000 A, which caused the cable to quench, followed by a rapid increase in cable and helium gas temperature (figure 17). Unfortunately, the data acquisition rate of 3 Hz was insufficient to record the maximum current in the cable. The current was already reduced to 4500 A within the measurement interval of about 0.3 s. The cables developed a voltage of about 5 V each, or a total voltage of 10 V over the two series connected poles within a timeframe of about 1 s. The current through the cable was reduced to about 2000 A when the power supply reached its output power limit within a timeframe 3.5 s after the start of the overcurrent event. The two-pole CORC® cable thus successfully acted as an FCL cable, reducing the overcurrent by 66%. The power supply was switched off manually after about 2 s from the start of the overcurrent event.

The temperature of the helium gas at the outlet of the cryostat increased from about 71 K to 200 K during the overcurrent event. The local temperature of the cable was likely higher. The maximum power generated within the

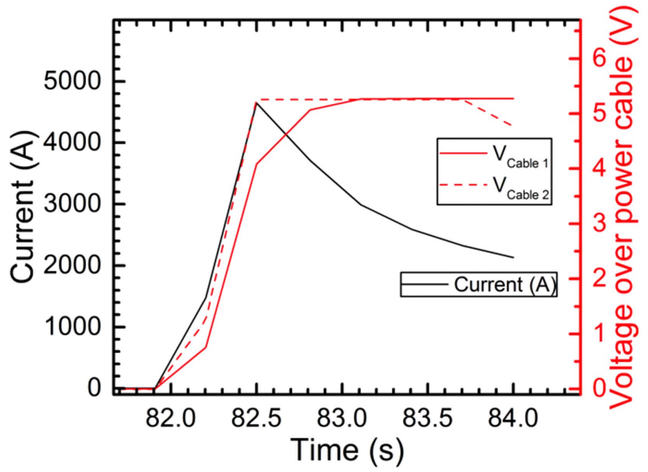

Figure 16. Current and voltage as a function of time of each of the two poles of cable CORC®-3 during the overcurrent event.

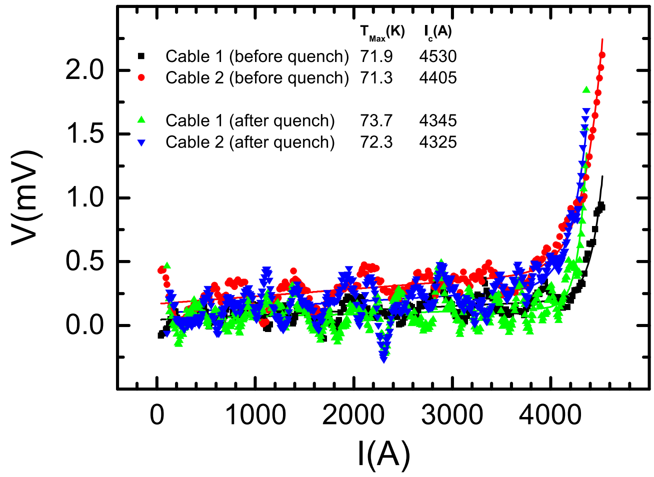

Figure 18. *VI*-curves of the two poles of cable CORC®-3 when connected in series before and after the overcurrent event.

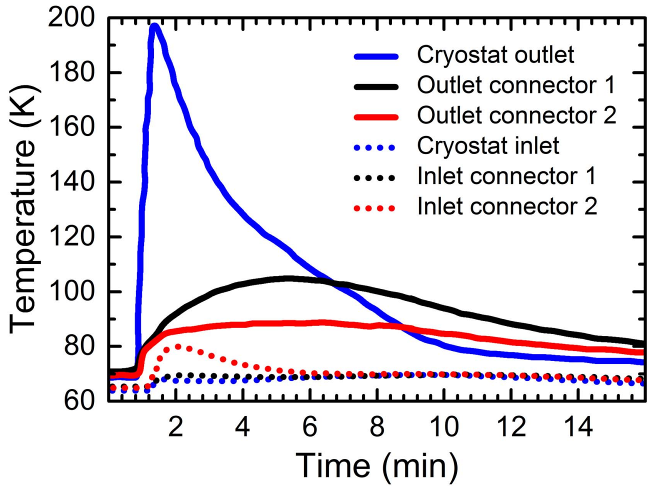

Figure 17. Temperature as a function of time of the two-pole operation of cable CORC®-3 during the overcurrent event that lasted 2 s.

system was about 43.4 kW and the total energy dissipated was 53.66 kJ. The helium gas that was injected back into the cryostat increased from about 62 K to 70 K within approximately 10 min, limited by the cooling power of the Stirling cryocooler. The *VI*-characteristics of the two-pole CORC® cable were tested after the temperature returned to within 1 K of the temperature before the overcurrent event was initiated. Figure 18 confirms that the cables did not degrade. Both poles had an I_c of about 4300 A or 200 A lower at a slightly higher temperature of between 72.3 K and 73.7 K compared to the measurement performed at 71.9 K before the overcurrent event.

The helium gas circulation system required more than 15 min to cool the power cable system back down to below 74 K, due to the combination of the high amount of energy that was deposited within the helium cryostat, the low thermal capacity of the helium gas and the limited cooling power of the helium circulation system. The CORC® cables could be optimized for FCL applications by reducing the amount of stabilizer present to speed up the cable's response time. In addition, optimization at a system level, such as increased cooling power or the integration of power electronic switches, could be used to isolate the cable to decrease its recovery time. The FCL cable could also be part of a hybrid cable system in which the CORC® FCL cable is connected in parallel to a normal cable at room temperature. Current would be diverted into the normal cable during an overcurrent event that causes the FCL cable to generate a significant voltage, allowing easier disconnection of the superconducting cable. Further development of faster CORC® FCL cables and wires will be described elsewhere [17].

4. Conclusions

High-temperature superconducting Conductor on Round Core (CORC®) cables offer a practical solution for power transmission applications that require very high power levels to be transmitted in compact and lightweight systems. CORC® cables allow current densities in excess of 200 A mm^{-2} in a highly flexible configuration. The result of several cable tests in which the cable was cooled in pressurized helium gas demonstrated the ability of CORC® cables to be operated without the use of liquid cryogens, while carrying currents as high as 6000 A in a cable of less than 7 mm in diameter.

A 1 m long CORC® cable was successfully tested in a temperature range between 62 and 77 K at currents of up to 2000 A, where a linear increase in critical current with decreasing temperature was measured. The results show that the critical current is expected to increase by a factor of 4.4 when the cable is cooled from 77 K down to 50 K, which is an operating temperature of interest to the US Navy.

A second test of a short CORC® cable in helium gas at currents up to 6000 A showed the ability of operating CORC® cables and connectors at high current with a resistive loss of less than 5 W per connection. The results demonstrate the possibility of operating helium gas cooled direct current CORC® power transmission cable systems at a very low cryogenic thermal load on the cryogenic system.

A 10 m long two-pole direct current CORC® power transmission cable was fabricated from two separate CORC® cables. The cables were integrated with custom terminations cryostats that contained two sets of feeder cables at each end of a flexible cryostat. The cable system was successfully tested in flowing helium gas at a pressure of 1.7 MPa and at a maximum temperature of about 72 K. Both poles were tested separately and while connected in series, where they had a critical current of about 4500 A each. The expected critical current of 12–13 kA at 50 K would allow a rated current of the cable system of 10 kA. The two-pole CORC® cable was also tested as a helium gas cooled fault current limiting cable. A total voltage of 10 V was generated at a maximum current of 6000 A, which was reduced to about 2000 A within 2 s after the fault started. A total energy of over 50 kJ was dissipated within the helium gas cryostat, raising the temperature of the gas to about 200 K. The cable recovered and showed no degradation due to the overcurrent and quench event. The results show that the high level of current sharing between tapes in CORC® cables allow their operation as fault current limiting cables without the need for additional stabilizer added to the tapes to prevent local burnout, even at reduced levels of cooling provided by helium gas compared to liquid nitrogen.

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References

[1] Demko J A, Sauers I, James D R, Gouge M J, Lindsay D, Roden M, Tolbert J, Willén D, Træholt C and Nielsen C T 2007 Triaxial HTS cable for the AEP bixby project *IEEE Trans. Appl. Supercond.* **17** 2047–50

[2] Weber C S, Lee R, Ringo S, Masuda T, Yumura H and Moscovic J 2007 Testing and demonstration results of the 350 m long HTS cable system installed in Albany, NY *IEEE Trans. Appl. Supercond.* **17** 2038–42

[3] Maguire J F, Yuan J, Romanosky W, Schmidt F, Soika R, Bratt S, Durand F, King C, McNamara J and Welsh T E 2011 Progress and status of a 2G HTS power cable to be installed in the Long Island Power Authority (LIPA) grid *IEEE Trans. Appl. Supercond.* **21** 961–6

[4] Maruyama O, Honjo S, Nakano T, Masuda T, Watanabe M, Ohya M, Yaguchi H, Nakamura N and Machida A 2014 Results of Japan's first in-grid operation of 200-MVA superconducting cable system *IEEE Trans. Appl. Supercond.* **25** 5401606

[5] Stemmle M, Merschel F, Noe M and Hobl A 2013 AmpaCity—installation of advanced superconducting 10 kV system in city center replaces conventional 110 kV cables *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices* pp 323–6

[6] Maguire J, Folts D, Yuan J, Lindsay D, Knoll D, Bratt S, Wolff Z and Kurtz S 2009 Development and demonstration of a fault current limiting HTS cable to be installed in the Con Edison Grid *IEEE Trans. Appl. Supercond.* **19** 1740–3

[7] Pamidi S, Kim C H and Graber L 2015 High-temperature superconducting (HTS) power cables cooled by helium gas *Superconductors in the Power Grid: Materials and Applications* ed C Rey (Cambridge: Woodhead Publishing) pp 225–60

[8] van der Laan D C, Noyes P D, Miller G E, Weijers H W and Willering G P 2013 Characterization of a high-temperature superconducting conductor on round core cables in magnetic fields up to 20 T *Supercond. Sci. Technol.* **26** 045005

[9] van der Laan D C, Weiss J D, Noyes P, Trociewitz U P, Godeke A, Abraimov D and Larbalestier D C 2016 Record current density of 344 A mm^{-2} at 4.2 K and 17 T in CORC® accelerator magnet cables *Supercond. Sci. Technol.* **29** 055009

[10] Weiss J D, Mulder T, ten Kate H J J and van der Laan D C 2017 Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications *Supercond. Sci. Technol.* **30** 014002

[11] van der Laan D C, Lu X F and Goodrich L F 2011 Compact $GdBa_2Cu_3O_{7-\delta}$ coated superconductor cables for electric power transmission and magnet applications *Supercond. Sci. Technol.* **24** 042001

[12] van der Laan D C, Goodrich L F and Haugan T J 2012 High-current dc power transmission in flexible $RE\text{-}Ba_2Cu_3O_{7-\delta}$ coated conductor cables *Supercond. Sci. Technol.* **25** 014003

[13] Mulder T, Dudarev A, van der Laan D C, Mentink M G T, Dhallé M and ten Kate H H J 2015 Optimized and practical electrical joints for CORC® type HTS cables *IOP Conf. Ser.: Mater. Sci. Eng.* **102** 012026

[14] Mulder T, Dudarev A, Mentink M G T, Silva H, van der Laan D C, Dhallé M and ten Kate H H J 2016 Design and manufacturing of a 45 kA at 10 T REBCO-CORC® cable-in-conduit conductor for large scale magnets *IEEE Trans. Appl. Supercond.* **26** 4803605

[15] Pamidi S, Kim C H, Kim J H, Crook D and Dale S 2012 Cryogenic helium gas circulation system for advanced characterization of superconducting cables and other devices *Cryogenics* **52** 315–20

[16] Tixador P and Nguyen N T 2012 Design of ReBaCuO-coated conductors for FCL *Supercond. Sci. Technol.* **25** 014009

[17] Weiss J D, Kim C, Pamidi S and van der Laan D C 2018 *Supercond. Sci. Technol.* submitted