Fault-Current Tests of a 5-m HTS Cable

J. W. Lue, G. C. Barber, J. A. Demko, M. J. Gouge, J. P. Stovall, R. L. Hughey, and U. K. Sinha

***Abstract*—The first industrial demonstration of a three-phase high-temperature superconducting transmission power cable at the Southwire manufacturing complex is in progress. One crucial issue during operation of the 30-m HTS cables is whether they could survive the fault current (which can be over an order of magnitude higher than the operating current) in the event of a short-circuit fault and how HTS cables and the cryogenic system would respond. Simulated fault-current tests were performed at ORNL on a 5-m cable. This single-phase cable was constructed in the same way as the 30-m cables and is also rated for 1250 A at 7.2 kV ac line-to-ground voltage. Tests were performed with fault-current pulses of up to 15 kA (for 0.5 s) with pulse lengths of up to 5 s (at 6.8 kA). Although a large voltage drop was produced across the HTS cable during the fault-current pulse, no significant changes in the coolant temperature, pressure, or joint resistance were observed. The cable survived 15 simulated fault-current shots without any degradation in its V-I characteristics.**

***Index Terms*—Critical current, current limitation, fault current, high-temperature superconducting cable.**

I. Introduction

SOUTHWIRE Company is demonstrating the world's first industrial application of high-temperature superconducting (HTS) power cables with a 30-m, three-phase cable system at its Carrollton, Ga., plant [1]. Oak Ridge National Laboratory (ORNL) worked very closely with Southwire in developing this cable system. An HTS cable test facility [2] was built and was used to test two 5-m single-phase cables for their dc and ac characteristics and the high-voltage integrity of the cold-dielectric design [3].

Another crucial issue for the operation of the 30-m HTS cables is whether they could survive the fault current (which can be over an order of magnitude higher than the operating current) in the event of a short circuit and how HTS cables and the cryogenic system would respond. Fault-current simulation tests were performed on the second 5-m HTS cable at the ORNL 5-m test facility. A 25-kA, 12-V dc power supply was reconfigured for this test. Tests were performed with fault-current pulses up to 15 kA for 0.5 s and 6.8 kA for 5 s. The cable survived all the fault-current pulses. We report in this paper the responses of the cable and the coolant during and immediately after the pulses.

II. Cable Response to Simulated Fault-Current Pulses

The cable was cooled down to about 81 K with liquid nitrogen (no pumping on the sub-cooler bath) at a pressure of about 4.7 atm and a flow rate of about 0.19 L/s (3 gpm). Short current pulses much larger than the critical current, I_c (about 910 A), of the cable were applied to the cable to simulate fault currents in case of an in-service short circuit. The voltages across the phase conductor and the joint, the current and voltage of the shield conductor, and the temperature and pressure of the coolant during the pulse and for a period after the pulse were monitored. Shots were made first with a 1-s pulse at increasingly higher current from 4.8 to 12.8 kA. The pulse length was then increased to 2 s, and again up to 12.8-kA current pulses were applied. The pulse length was shortened to 0.5 s and a current of 15.3 kA was applied. Finally, the pulse length was lengthened to 5 s and a current of 6.8 kA was applied.

A. Cable and Joint Voltages

Fig. 1 shows the current and voltage traces of the cable on a typical shot. A fault-current pulse of about 12.8 kA was programmed to apply to the cable for 2 s. As soon as the current reached 12.8 kA, a voltage (V-cable) of about 3.2 V was developed across the cable. This and the voltage drops along the terminations and external power supply cables had apparently exceeded the power supply limit (12 V) and caused the current to drop. By the end of the 2-s pulse, the current was lowered to about 6.9 kA. However, the cable voltage continued to rise to over 5 V, indicating heating in the conductor. On the other hand, the cable-to-connector joint voltage (V-joint) was lowered from about 0.3 to 0.17 V in the same proportion as the current drop.

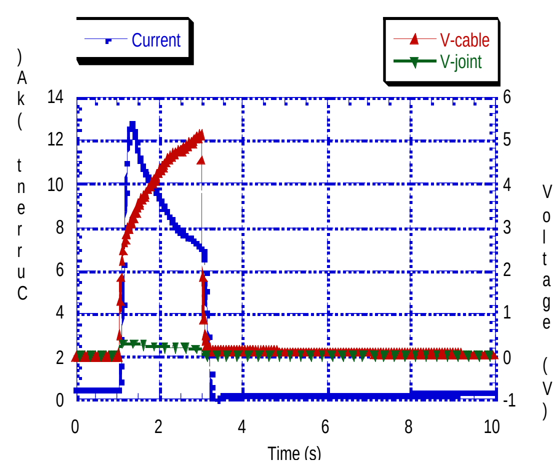

Fig. 1. Cable (phase conductor) and joint voltages in response to a 12.8-kA, 2-s fault-current pulse.

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B. Cable and Joint Resistances

The cable voltage rise indicated that a temperature rise had occurred. To see more clearly how the cable heated up during the fault-current pulse, we divided the measured voltage by the corresponding current to get the resistance response of the cable. The result is shown in Fig. 2. It is seen that at the beginning of the 12.8-kA pulse, the cable resistance went to 0.25 mΩ (as compared to 0.54 μΩ at critical current) and increased to 0.72 mΩ by the end of the 2-s pulse. (The discontinuity at the beginning and end of the current pulse was due to dividing the cable voltages by the near zero currents.) Based on the silver resistivity change as a function of temperature, the above resistance change of the cable indicated that the HTS conductor had heated to about 170 K by the end of the pulse. Although the cable voltage nearly disappeared after the current pulse in Fig. 1, its resistance in Fig. 2 showed a relatively slow cooldown to about 0.1 mΩ 7 s later.

Note that in the construction of the cable, the HTS tapes are separated from the coolant on the ID with bedding tapes and a corrugated stainless tube and on the OD with layers of Cryoflex dielectric tapes. Thus, cooling of the HTS tapes is essentially by conduction only. The heating of the HTS tapes during the fault-current pulses can be approximated as adiabatic. Integrating the product of current and voltage (the power) over the pulse in Fig. 1, we found the total energy generated in the conductor in this shot to be about 80 kJ. Using the silver-specific heat integral, we estimated that the conductor would heat up to about 175 K adiabatically. This is consistent with the above estimated temperature rise based on the observed resistance increase. Note also that Fig. 2 indicated that the joint resistance remained at 24 μΩ throughout the shot. Thus, there was no noticeable temperature rise on the joint because of its better cooling condition (with direct contact with LN_2).

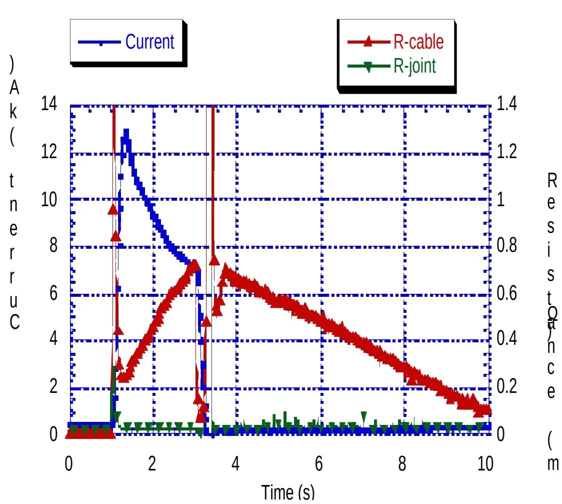

Fig. 2. Cable (phase conductor) and joint resistances in response to a 12.8-kA, 2-s fault-current pulse.

C. Cable Resistance in the Over-Current Regime

The fact that, in response to an over-current, the cable resistance becomes much higher than its value at I_c means that the HTS cable possesses an intrinsic current limitation function. Determining the extent of the cable resistance rise during an over-current will tell the extent of the current limitation offered by the cable. From the moments the different pulsed currents reached their peaks, we found the cable resistance at all 15 over-current shots. The result is shown in Fig. 3 as a function of current. Note that the 5-m cable resistance increased rapidly from 0.54 μΩ at I_c to 0.31 mΩ at 15.3 kA—nearly 600 times higher.

The dc V-I curve (see Fig. 4) showed that above I_c the voltage of the present superconductor increases in proportion to I to the 3.8th power (the n-value). Thus, the resistance of the superconductor at an over-current, I, can be scaled from its value of 0.54 μΩ at I_c by a factor of $(I/I_c)^{2.8}$. In addition to the superconductor, the present HTS tape contains 70% of silver in the composite. Using a resistivity of 0.3 μΩ-cm, we

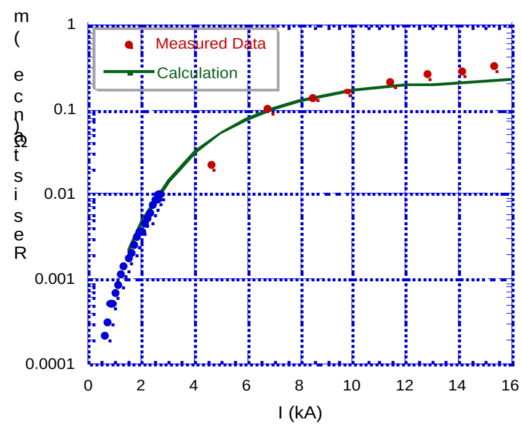

Fig. 3. Cable (phase conductor) resistance as a function of current. The data below 2.8 kA were taken from slow dc run shown in Fig. 7.

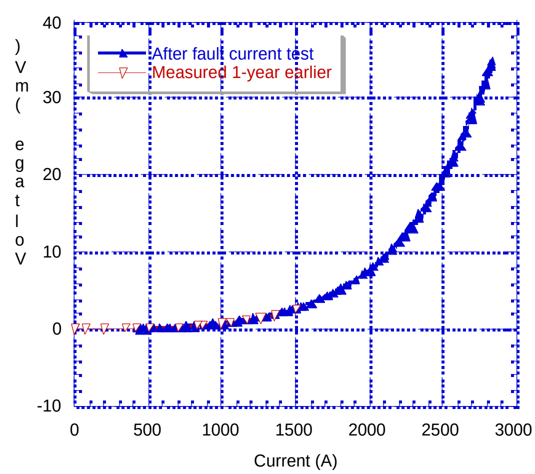

Fig. 4. The V-I curve of the cable after the fault-current tests compared with an earlier measurement.

estimated the resistance of the silver matrix in the cable to be about 0.25 mΩ at liquid-nitrogen temperature. The cable resistance in the over-current regime was then calculated by paralleling the scaled HTS resistance with the silver resistance. The result is shown as the calculated curve in Fig. 3. It is seen that the measured data follow the calculated curve very well—proving that the power-law scaling of the HTS resistance above I_c is appropriate.

The above analysis indicates that the HTS in the present cable shared the fault current equally with the silver matrix at 8.1 kA—about nine times the critical current. Below this value the current flows mostly in the superconductor; above this value more and more current flows in the silver matrix. At 15 kA, the HTS can carry only 15% of the fault current. It is also noted that above 10 kA the measured data lay above the calculated curve, indicating tape heating before the fault current reached its peak value.

III. Coolant Response to Simulated Fault-Current Pulses

A. Measured Temperature Changes

Because of the high-voltage drop developed across the cable during a fault over-current, the power is high and the total energy dissipation can be significant when the pulse length is long. When this energy is dumped into the coolant, the temperature and the resulting pressure rise may upset the cooling system. The shot shown in Fig. 1 produced the highest energy dissipation of all the shots. In Fig. 5, the responses of the temperature sensors are shown for this shot. The sensor "T-out" is located near the coolant outlet of the cable inside the termination, and "T-far" is located at the cable side of the far-end termination. Neither of these sensors in the flowing coolant showed any temperature rise during or after the current pulse. Only the "T-bus," sensor, which is located at the bus side of the far-end termination, showed a temperature rise of about 5 K, 3 s after the pulse. This sensor was cooled by stagnant gas and was at a higher temperature of about 96 K.

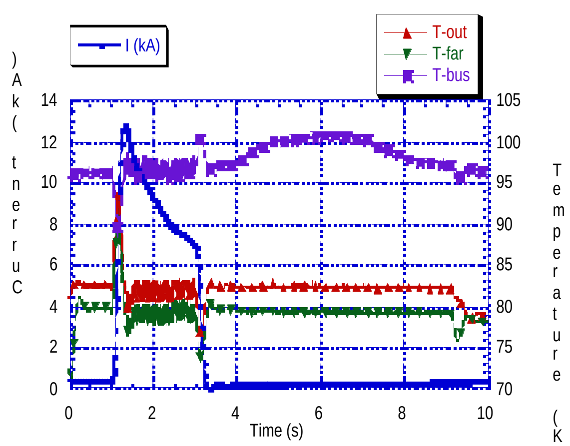

Fig. 5. Temperature responses of the various sensors for the 12.8-kA, 2-s over-current pulse.

As was stated above, the total energy produced in the cable in this shot was about 80 kJ. If half of this energy were dumped instantaneously into the liquid nitrogen in the inner pipe (the former) of the cable the temperature would rise by about 5 K. No such temperature rise was observed. The phase conductor was not cooled directly by the coolant, and it took tens of seconds for the conductor to cool (and thus to release heat to the coolant). Furthermore, the liquid nitrogen flow rate of about 0.2 m/s inside the pipe replenished the coolant fast enough to prevent any measurable temperature rise in the coolant.

B. Measured Pressure Changes

Figure 6 shows the corresponding pressure changes in the same shot. Contrary to the temperature response, it is seen that both the inlet and outlet pressure started to rise 1 s into the pulse and reached a peak value of about 0.34 atm (5 psi) at 1 s after the pulse. Both pressure taps were meters away from coolant inlet and outlet of the cable. Apparently, the pressure wave reached them in a fraction of a second (with the speed of sound in liquid nitrogen). Since no temperature rise in the coolant was observed, we infer that the pressure rises resulted from transient heating in the terminations.

Over the 1-h span of the 15 simulated fault-current shots, the accumulated temperature rise of the cable outlet coolant was found to be about 1 K, and there were no significant system pressure changes. Thus, repeated fault-currents that are separated minutes apart would not upset the present HTS cable or the cryogenic system.

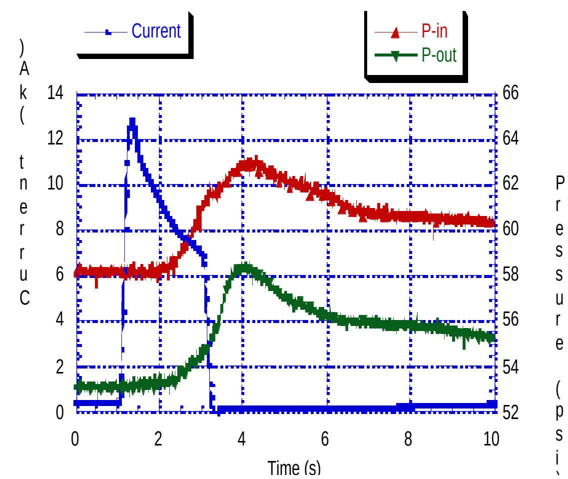

Fig. 6. Pressure changes in the coolant for the 12.8-kA, 2-s fault-current pulse.

IV. Shield Loop Voltage and Current

The voltage and current induced in the shield loop by the fault current in the phase conductor are other concerns. In the experiment, the two ends of the superconducting shield were tied together with copper cable and a current shunt to monitor the induced current. Fig. 7(a) shows the induced current in the shield loop for the 12.8-kA, 2-s fault-current shot. Only about 350 A and 120 A of transient currents were induced in the shield at the rise and fall of the phase conductor over-current. Part of the reason for these low values is due to the relatively long rise and fall time (of about 300 ms) of the over-current provided by the present power supply. If a fault current would rise faster, the induced transient in the shield would be higher. During the 2 s of slow decrease of over-current, there was no measurable induced current in the shield.

Figure 7(b) shows that the maximum voltage developed over the shield conductor was less than 0.35 mV. Since this voltage is lower than the critical-current voltage of 0.5 mV for this cable and the induced transient current was lower than the critical current, we determined that the shield conductor stayed superconducting during the fault-current pulses.

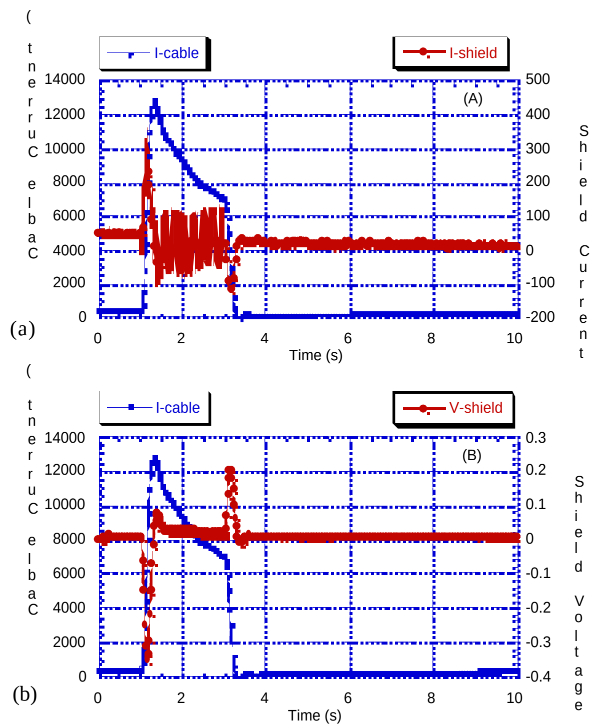

Fig. 7. Induced current and voltage in the HTS shield for the 12.8-kA, 2-s fault-current pulse.

V. DC Characteristics of the Cable

To determine whether there was any significant degradation of the cable from the simulated fault-current shots, the dc V-I curve of the cable was measured after the fault-current tests. Figure 4 shows the present V-I curve of the cable compared with a measurement made a year earlier. There is no difference in the two V-I curves. Note that between these two dc V-I measurements, the cable was subjected to high-voltage withstand tests to 18 kV, impulse tests to 90 kV, long-duration (72-h) testing at the design current and voltage, and tens of cool-down and warm-up cycles [3], [4]. The cable showed no degradation in its dc characteristics throughout these tests. At the criterion of 1 μV/cm, the critical current of the cable remained at about 910 A.

VI. Summary

In summary, fault-current simulation tests were performed at ORNL on the second 5-m HTS cable built by Southwire. A sequence of 15 shots of fault-current pulses was applied to the cable with peak current up to 15 kA—more than 10 times the design current (for 0.5 s) and pulse lengths up to 5 s (at 6.8 kA). The cable survived all the fault-current pulses. A high-voltage drop (several volts as compared to 0.5 mV at I_c) was developed across the cable during the pulse that led to a drop of the fault current. The HTS cable resistance increased by two to three orders of magnitude in the presence of the fault currents. More than a 50% drop in fault current was observed. Thus, the HTS cable possessed an intrinsic current-limitation function.

No measurable temperature rise, and only about 0.34 atm of pressure rise were observed in the liquid nitrogen coolant during all the fault-current shots. This is due in part to the fact that the phase conductor HTS tapes were not in contact with liquid nitrogen. The cryogenic system was not upset by any of the fault-current shots or by the accumulated effects of the shots over the 1-h test period. It was also noted that the induced current and voltage on the HTS shield conductor were minimal.

The dc voltage-current measurements showed no degradation in the HTS cable from the earlier high-voltage, high-current tests, thermal cycles, and the present fault-current tests.

The 30-m HTS power cable demonstration facility at Southwire is protected by breakers rated at 13 kA for 0.7 s and 8 kA for 1 s. The present laboratory simulation fault-current test results give confidence that the in-service 30-m HTS cables will survive fault currents due to any foreseeable short circuit and that the cryogenic system will not be adversely disturbed by such events.

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