Progress and status of cryogenic refrigeration system for project Hydra

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Abstract. In the last two decades, HTS cables have been successfully demonstrated around the world, preparing HTS power cables for a full commercial introduction. Among the demonstration projects, circulating subcooled liquid nitrogen to maintain the HTS cable at operating temperature is a widely adopted approach. In this approach, the cooling systems are absolutely critical to the successful operation of the HTS cables. This paper describes the progress and status of the cryogenic refrigeration system designed and manufactured for project Hydra, which is a project jointly funded by the U.S. Department of Homeland Security Science and Technology Directorate, American Superconductor and Consolidated Edison Company of New York, Inc. American Superconductor is leading the team supported by Con Edison, Ultera, Altran Solutions, and DH Industries. The cable is an inherently fault current limiting HTS cable, approximately 200 m long and designed to carry 96 MVA at a distribution level voltage of 13.8 kV. The cable will be installed and energized near New York City. The refrigeration system was designed and manufactured by DH Industries. This paper provides details on the successful factory acceptance testing completed in November 2014.

1. Introduction
In last two decades, there is a growing demand for a reliable and sustainable electric power infrastructure all over the world. Such infrastructure is a key requirement for large, densely populated urban areas that are traditionally host to critical centers of finance, trade and government, where significant disruptions to the electric power grid can severely impact the regional and national economy and security. High Temperature Superconducting (HTS) cables have long been considered an enabling technology for high density and secure power transmission. HTS cables have been successfully demonstrated around the world [1], [2], [3], preparing HTS power cables for full commercial introduction. However, to enable HTS power cables, a cooling system is necessary, which is usually bulky in size and complicated to operate [4]. The reliability and availability of the cooling system and its footprint are always concerns of the end utility users, especially for dense urban areas, where accessibility and space for equipment installation are always limited. In this paper, a closed-loop refrigeration system, using on-site mechanical refrigerators for both primary and back-up system, has been designed and manufactured. In this approach, a large, permanent on-site liquid nitrogen (LN2) tank is eliminated. To enhance the reliability and availability of the cooling system to the HTS cable system, tremendous efforts have been made to improve the system’s resiliency under a variety of contingencies such as during an electrical blackout and loss of all refrigeration cooling power. DH
Industries designed and manufactured the refrigeration system which successfully passed factory acceptance testing in November 2014. Details of the test results are provided.

2. Project Hydra overview

Project Hydra is intended to develop and demonstrate an HTS cable with built-in fault current limiting capability. The cable will connect two substations to share the assets and is approximately 200 m long at rated current of 4000 A and voltage of 13.8 kV. The cooling system developed and manufactured by DH Industries will supply 6.2 kW of cooling power at 72 K with a liquid nitrogen flow rate of 90L/min. The underground cable will provide a major advancement in power capacity and fault current protection, while adding to the security and reliability of the electric power grid.

3. Refrigeration system description and specification

The refrigeration system for Project Hydra is a closed-loop system based on using Stirling Cryocoolers in conjunction with a liquid nitrogen sub-cooler. Figure 1 shows a simplified flow diagram of the cooling system. The key features of this system include three Stirling cryocoolers, three water chillers, three LN2 pumps, one low pressure tank (sub-cooler), one high pressure tank (buffer) and control valves. In this particular configuration, three Stirling cryocoolers are placed on the top of a sub-cooler through flexible vacuum jacketed lines to control the sub-cooler pressure and therefore the tank temperature to control the LN2 loop supply temperature. The buffer is utilized to control the LN2 loop pressure and also used to relieve or compensate for the volume changes of the LN2 in the cable system when fault conditions occur. Under normal operating conditions, the system will operate two Stirling cryocoolers and two LN2 pumps to maintain the HTS cable at its operating temperature.

![Figure 1. Simplified flow diagram of Hydra refrigeration system.](image)

To ensure the refrigeration system availability, an N-1 component redundancy scheme is adopted in the current project in case of contingencies. The N-1 scheme allows the system to operate normally even when one of the critical components is out of service due to either failure or required maintenance. The critical components include the on-site mechanical refrigerator, LN2 pump, water chiller for the mechanical refrigerator, measurement sensors, instrument air and electric power to the control panel and liquid nitrogen pump. The back-up power for the control panel can last eight hours while the back-up power UPS for the LN2 pumps can only last 30 minutes. The Hydra project established as key evaluation criteria that transitions between primary and back-up components must be automatic and not create any adverse transient conditions that could affect the performance and reliability of the HTS cable system. To enable the HTS cable to operate continuously even in the case of contingencies, logic has been implemented in the refrigeration system controller to recognize an
abnormal event and respond appropriately. For example, the refrigeration system controller can detect the failure of a Stirling cryocooler and switch the cooling duty to the redundant standby unit automatically. The liquid nitrogen supply temperature and system pressure during this transition are tightly controlled such that the performance of the HTS cable is not being affected. In the event of a power failure, or power interruption, the refrigeration system is designed to switch on automatically when the power resumes in less than five minute. The detailed specifications for the Hydra refrigeration system are listed in the Table 1.

| Item                                      | Specification                  |
|-------------------------------------------|--------------------------------|
| Total heat load (excluding refrigeration system) | 6.2kW @ 72K                   |
| Cable inlet pressure (maximum)            | 18 +/- 0.3 bar, absolute       |
| Cable outlet pressure (minimum)           | 16 +/- 0.3 bar, absolute       |
| Refrigeration system internal pressure drop | < 0.5bar                      |
| Subcooled LN2 flow rate                   | 90L/min                       |
| Cable inlet temperature                   | 72K +/- 0.5K                  |
| Subcooled LN2 filtering                   | 100 micron                    |

4. Factory acceptance tests
The refrigeration system has been tested in the factory of DH Industries in Eindhoven, Netherlands according to the refrigeration specifications. A variety of tests have been carried out including soft cool-down, cooling capacity, heat load variation, critical components switching and recovery from main supply power blackout.

4.1. Test Setup
The refrigeration system was assembled in the factory to mimic the final installation on site with a few exceptions. The first exception was a 6 m dummy U-turn pipe section, a few restriction valves and an internal bypass heater were used to simulate the 200 m HTS cable. The restriction valves were used to simulate the pressure drop along the HTS cable and terminations while the internal heater was used to simulate the HTS cable heat load as shown in figure 2. The 6 m dummy U-turn pipe section was only used for the cool-down test while the internal bypass heater was used for the remaining tests. The second exception was a large single water chiller was used to provide cooling water for all three
Stirling cryocoolers instead of three individual chillers. Finally, the backup UPS was simulated by available utility power at the factory.

4.2. Cool-Down Test

Since the installation is in a dense urban area, using on-site mechanical refrigerators to cool-down the cable without an on-site liquid nitrogen tank is one of the main objectives of this demonstration project. To avoid a large LN2 tank and dumping LN2 at the site, the initial cool-down of the cable system will rely on the on-site mechanical refrigerators. The cool-down process includes three steps. The first step is to circulate nitrogen gas through the cable system by using the mechanical refrigerators and high pressure buffer. During the factory acceptance testing, the buffer pressure was used as a driving force instead of using the LN2 pump to circulate gaseous nitrogen through the dummy U-turn pipe section and the supply temperature was controlled by the internal cool-down heater (not shown in figure 2.). The warm return nitrogen gas was re-condensed inside the low pressure sub-cooler by the mechanical refrigerators. When the LN2 level inside the buffer is low, the connection valves between the buffer and the sub-cooler are opened, and the buffer is re-filled from the sub-cooler. After refill, the cool-down process continues until the system reaches a pre-determined temperature (~80 K), and then saturated LN2 from portable dewars are used to fill the dummy U-turn. During this process, the LN2 pump is utilized to circulate LN2, and the buffer is used as a phase separator. Finally, the system is pressurized and sub-cooled to its final operational conditions by the main refrigeration system.

Figure 3 shows the supply and return temperatures during the cool-down with the dummy U-turn pipe section and pressure profiles of the buffer and sub-cooler. As seen by the pressure profiles, during the entire cool-down process, the buffer was refilled two times. Due to the short length of the dummy U-turn, the total cool-down time is only a few hours. The expected cool-down time for the final installation is around 3 to 4 days. The temperature set points during the test were 200 K, 150 K, 100 K and 80 K as be seen by the Supply temperature profiles.

![Figure 3](image-url)

**Figure 3.** The supply and return temperatures and pressures in buffer and sub-cooler during cool-down.

4.3 Cooling capacity and load variation test

To test the system nominal cooling capacity, the dummy U-turn was shunted by a self-test heater. The maximum heater capacity was 8.8 kW, which provided enough heating power to test all three...
cryocoolers at the same time. Figure 4 shows the supply and return temperatures during the 14 hour test period. As shown, the temperature stayed in a very tight range. The overall variation was less than +/-0.1 K. The buffer tank pressure variation was less than +/-0.2 bar during the same test period. The LN2 flow rate was 90 L/min during the entire test period. Based on the flow rate and temperature rise, the calculated cooling power is 6.214 kW, which is in agreement with the electrical power input.

![Figure 4. Supply and return temperatures, buffer tank pressure over 14 hour test period.](image)

A partial cooling power test was carried out by setting the heat load to 55% of the full cooling power, where one cryogenerator was fully engaged and one cryogenerator was partially engaged. The test configuration was the same as before, but with the self-test heater input power set at 3.4 kW. The nominal flow rate was around 90 L/min. The temperature and pressure were recorded during the entire test period. The temperature variation was around +/-0.3 K while the pressure variation was around +/-0.2 bar.

![Figure 5. Temperature and pressure vs. time during load altering test.](image)

The heat load variation test was carried out to check the refrigeration system capability to reliably altering its cooling output several times every day to accommodate the cable load changes. The heat load was changed from 3.4 kW to 6.2 kW for 2 hours and then changed back to 3.4 kW. Figure 5
shows the supply and return temperatures during the load alteration from 3.4 kW to 6.2 kW and from 6.2 kW to 3.4 kW. The temperature and pressure variations during the load switching were both in the specified range. The refrigeration system demonstrated its capability to reliably alter its cooling output.

4.4 Redundant components switching test
To check the control logic design for transitions between use of primary components and back-up components, all redundant components were tested including: LN2 pump, Stirling cryocooler and water chiller. As mentioned before, there is only one large chiller to supply cooling water for all three cryocoolers, the chiller redundancy test was done by simply shutting off the cooling water supply to that specific cryocooler.

All the tests were done by manually shutting off a component and watching the corresponding redundant component switch on. All parameters were recorded during the entire switching process. During all of the tests, a 6.2 kW heat load was applied to the self-test heater to simulate the cable load.

To make the redundant LN2 pump switch in as quickly as possible, it was necessary to keep the redundant pump cold (e.g., near its normal operating condition), and therefore, no cool-down time was required. This was accomplished by using a thermal syphon effect between the vapor and liquid phase inside the buffer tank. The buffer tank was used to provide liquid to the pump and the small parasitic heat loss of the pump is carried out by the liquid stream and returned to the buffer tank as vapor with the appropriate valve arrangements. Figure 6 shows the temperature and pressure during the pump switching. As seen, the entire switching process took about five minutes, and the effects on the supply temperature and system pressure were minimal.

Figure 6. Buffer pressure and flow rate vs time during LN2 pump switching.

Figure 7 shows the temperature and pressure during the cryocooler switching test. In this specific test, cryocooler 2 was manually shut off and standby cryocooler 3 was switched in immediately. Initially, the LN2 supply temperature started to rise since the standby cryocooler was warm. After about five minutes, the LN2 supply temperature started to drop. The LN2 supply temperature rose about 0.5 K during this switching and then took about 1.5 hours to recover to the normal state. The buffer pressure was relatively stable during the switching as illustrated in Figure 7.

The water chiller switching test was performed in a manner similar to the cryocooler switching test, where the cooling water supply valve was shut off manually and the corresponding cryocooler was shut off by the control panel detecting an insufficient cooling water flow rate. The test results were almost the same as the cryocooler switching test as shown in figure 7.
4.5 LN2 pump backup UPS test
When the main power to the refrigeration system is lost, the system will utilize the LN2 thermal mass inside the sub-cooler to keep the cable system cold as long as possible. To accomplish this, the system was designed with a back-up UPS which enables the LN2 pumps to run for 30 minutes after loss of power to the refrigeration system. There are two reasons for this approach. The first one is to prevent the HTS cable from warming up too fast and then relieving LN2 inventory. The second one is to provide extra time for the operator to shut down the system in a controlled manner. To simulate the cable heat load, a 6.2 kW heater was turned on. The test was done by switching off all the cryocoolers manually and leaving the LN2 pumps running about half an hour and observing the temperature and pressure changes during this time period. As seen in figure 8, the total time without any cryocoolers was roughly 35 minutes. The temperature rise during the 35 minutes was about 3 K while the buffer pressure variation during the entire test period was in the range of +/- 0.3 bar.

Figure 7. Pressure and temperature profiles vs. time during cryocooler switching.

Figure 8. Temperatures and pressure profile vs. time when all refrigerators were shutdown.
4.6. System recovery from blackout
This test was carried out to ensure that in the event of a power failure or interruption the refrigeration system will switch on automatically if the interruption interval is less than five minutes. The test was done by manually switching off the main power supply to the refrigeration system and switching power back on in less than five minutes. During the test, a heat load of 6.2 kW was applied to simulate the full cable system load. The system was successfully re-started without any glitches.

5. Conclusion
An HTS cable with inherent fault current limiting capability is currently under development with financial support from the U. S. Department of Homeland Security Science and Technology Directorate. The refrigeration system designed and manufactured for the HTS cable system successfully passed factory acceptance testing in November 2014. The refrigeration system has been shipped and will be installed on site when the site preparation is completed.

The Hydra project will be the first HTS cable with a built-in fault current limiting feature installed in an operating electric power grid and will be the first to demonstrate a path to greater system security and fault current control in a dense urban environment.

6. Acknowledgment
The authors wish to thank the U.S. Department of Homeland Security Science and Technology Directorate for their support.

7. References
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