Installation of Pulse Tube Cryocoolers for Cooling of HTS Cable

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Abstract. Praxair, Inc. has provided cooling to the HTS cable at the Bixby Road substation in Columbus, Ohio for the past year. The refrigeration has been supplied by an open-loop liquid nitrogen system. Data collected during system operation indicate that the average heat load from the HTS cable is 1.6 kW and the average total heat load on the system is 4.9 kW. In order to more effectively provide HTS cable refrigeration, Praxair has developed a large capacity Stirling-type pulse tube cryocooler. Performance testing of prototype and initial production models of the pulse tube coldhead has demonstrated a refrigeration capacity for nitrogen subcooling of 1 kW at 77 K when a 20 kW, dual-opposed pressure wave generator is used to generate acoustic power for the cryocooler. The initial production models of this pulse tube refrigerator are ready for deployment for field testing at Bixby Road. Operation of these pulse tube units will reduce the nitrogen consumption of the open-loop cooling system and data on the reliability and performance of the cryocoolers will be collected.

1. Introduction
As increased demand for electricity strains the capacity of electric grids around the world, infrastructure must be improved to enable the reliable delivery of electric power. One technology that offers a solution to this problem is high temperature superconducting (HTS) cables. HTS cables can carry up to five times more power than a conventional cable, and in many cases operate at a lower voltage. They can also be installed in existing rights-of-way currently used for conventional cable. For instance, an HTS cable operating at 50 kV can carry 250 MVA through the same right-of-way as a conventional cable that can carry 100 MVA at 150 kV. These capabilities are ideal for the supply of power to congested urban centers, where rights-of-way are difficult and expensive to obtain. Operation of the HTS cable at a typical distribution voltage will also eliminate the need for transformers at the cable’s termination, opening up valuable urban real estate.

Several projects are underway to demonstrate the technical feasibility of the transmission and distribution of electricity using HTS cables [1]. One of these, funded by the Department of Energy, is located at American Electric Power’s (AEP) Bixby Road substation outside Columbus, OH. At this site, a 200 meter HTS cable manufactured by Ultera carries up to 69 MVA of power at 13.2 kV from a 138 kV to 13.2 kV transformer to a 13.2 kV distribution bus. More than 8,000 AEP customers have been served by electricity supplied through this cable since it entered operation in August 2006. Several larger-scale HTS cable projects are planned for the near future, providing opportunities for the development and verification of new technologies. Among these are the Hydra Project in Manhattan funded by the U.S. Department of Homeland Security, an Entergy project in New Orleans co-funded by the U.S. Department of Energy, and a Nuon project in Amsterdam [2].

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To date, one of the challenges associated with the adoption of HTS cables is the need for cryogenic refrigeration systems with low maintenance requirements, high reliability, small footprint, and acceptable cost. A variety of cooling systems have been used at the existing HTS cable installations, including reverse-Brayton cycle and Stirling cycle cryocoolers. The cable at Bixby Road is currently cooled by an open-loop liquid nitrogen system, and extensive operating data have been collected for this system. Stirling-type pulse tube cryocoolers have long been considered another option for providing cooling to an HTS cable, and recent developments by Praxair confirm the viability of this option. The cooling capacity of large-scale pulse tube cryocoolers was measured by laboratory testing, and installation of these coolers at the Bixby Road substation to supplement the open-loop system will demonstrate the feasibility of using pulse tubes as the sole source of refrigeration for cooling a HTS cable.

2. Operation of an Open-Loop Cooling System for a HTS Cable
Praxair provided an open-loop liquid nitrogen cooling system for the HTS cable at Bixby Road. In this design, sub-cooled liquid nitrogen is circulated through the cable in a closed loop by redundant cryogenic pumps. Heat is added to the liquid nitrogen by A/C losses in the cable, losses at the cable terminations, heat leak into the cryostat and heat leak in the cooling system. This heat is removed from the pressurized liquid nitrogen by passing it through a coil in a vessel filled with liquid nitrogen at sub-atmospheric pressure. The nitrogen in the vessel is maintained below atmospheric pressure through the use of vacuum pumps, and this sub-atmospheric condition allows temperatures below 77 K to be achieved. As the pressurized liquid nitrogen is cooled, it boils sub-atmospheric liquid nitrogen in the vessel. The vapor is removed by the vacuum pumps, and fresh liquid nitrogen is added to the vessel as necessary. A block flow diagram of the system is shown in figure 1 and a photograph of it is shown in figure 2.

**Figure 1.** Schematic flow diagram of the open-loop cooling system installed at Bixby Road. The location of the pulse tube cryocoolers in the system, as described in section 4, is shown in the figure.

Installation of the open-loop cooling system was completed in June 2006, and the system was tested extensively prior to the HTS cable being energized in August 2006 [3]. The system has operated satisfactorily since that time. Through July 2007, there have been three unplanned outages and one planned maintenance shutdown. The HTS cable was never allowed to warm up during this
period because the backup system maintained it at the appropriate temperature when the cooling system was off-line.

Operating data from Bixby Road for the period from February to July 2007 are shown in figure 3. The current draw through the cable is shown in this figure along with the heat load on the system. Two values of heat load are displayed: the heat load from the cable, including the cryostat and terminations, and the total system heat load, including pump energy and heat leak in the piping. These heat loads are calculated from the flow rate of the liquid nitrogen and the temperature rise between the ends of the cable and between the outlet and inlet of the circulating separator, respectively. The heat load from the cable averages 1.6 kW, while the total system heat load averages 4.9 kW. The non-cable refrigeration losses in the system average about 3 kW.

The open-loop cooling system has provided reliable refrigeration at Bixby Road, but other cooling solutions are necessary for HTS cable technology to be commercially viable because the open-loop
system has a large footprint and it requires frequent deliveries of liquid nitrogen. (Nitrogen is delivered to Bixby Road in batches of 7,500 gallons approximately once every 3 – 4 days.) One potential solution for providing refrigeration to the cable is the use of pulse tube cryocoolers, which are the basis of a closed-loop system (no liquid nitrogen deliveries) in a much smaller footprint.

3. Design and Testing of a 1 kW Pulse Tube Cryocooler

Praxair is currently engaged in developing the world’s largest Stirling-type pulse tube cryocoolers. The most recent model, shown in figure 4, was designed to achieve 1 kW of cooling at 77 K. The cryocooler consists of three main parts: a pressure wave generator (PWG), a coldhead and an inertance network. The PWG converts electrical power into acoustic energy. The coldhead and inertance network provide the proper phasing between pressure and mass flow in the system so that cooling is produced in the cold heat exchanger (CHX) of the coldhead.

Praxair’s 1 kW class cryocoolers utilize a Q-Drive 2S362W PWG manufactured by Clever Fellows Innovation Consortium. This PWG is nominally rated for 20 kW of input power.

The coldhead and inertance network for the cryocooler were designed by Praxair. The coldhead contains standard pulse tube components (from bottom to top): aftercooler, regenerator, CHX, thermal buffer tube (or pulse tube), and warm heat exchanger (WHX). The aftercooler, CHX, and WHX are shell and tube type heat exchangers with a staggered tube arrangement to maximize heat transfer. The regenerator is a stack of sintered 304-stainless steel screens.

![Figure 4. Three-dimensional model (left) and photograph (right) of a Praxair kilowatt class pulse tube cryocooler.](image)

The performance of the cryocooler was tested by subcooling saturated liquid nitrogen that passed through the process side of the CHX [4]. Nitrogen temperatures to and from the CHX were measured using RTDs placed inside the process lines. The flow rate of liquid nitrogen from a 160 liter dewar was controlled by varying the head space pressure in the dewar. Nitrogen flow was measured by a Foxboro Coriolis mass flow meter as well as by recording the change in mass of the dewar with time. Power measurements were made using a Hioki power meter and redundant Fluke current clamps.

An energy balance on the liquid nitrogen flowing through the process lines was used to rate the performance of the cryocooler. The average power input into the PWG was 24 kW. The ratio of the input power to the measured cooling power is shown in figure 5 for several liquid nitrogen outlet temperatures. At 77 K, this ratio is 21.9, indicating that the cryocooler produces 1100 W of cooling at this temperature with 24 kW of input power. This performance exceeds the design goal of 1 kW. The refrigeration at 77 K is achieved with an efficiency of 13% of Carnot.
4. Installation of Pulse Tube Cryocoolers for Cooling a HTS Cable

The performance measured for the cryocoolers described in section 3 indicates that each one can produce approximately 800 W of cooling at 70 K, the operating temperature of the liquid nitrogen entering the HTS cable at Bixby Road. Praxair has currently manufactured two of these cryocoolers. Although the two cryocoolers cannot provide all the cooling necessary for the cable, the 1600 W that they can deliver will reduce the load on the open-loop system by approximately 30%. The two cryocoolers will be installed in parallel with the open-loop system as shown in figure 1 and figure 6. They will also be installed in parallel with each other, so that each unit can operate independently.

Installation of the pulse tube cryocoolers is scheduled for September 2007. Once the units are installed, they will be monitored in order to optimize their operating parameters and measure the heat leak that they add to the system.

In addition to reducing the load on the open-loop system, the installation of the cryocoolers at Bixby Road is important to demonstrate the feasibility of field installation of pulse tube machines. Praxair’s pulse tube coolers have many advantageous features that make them ideal for use in HTS cable cooling applications, including a PWG with no wearing parts and a maintenance interval of more than 10 years, a coldhead with no moving parts and no planned maintenance, environmentally-friendly helium as a working fluid, low vibration and a small modular footprint. Successful operation of these units on the Bixby Road cable will demonstrate the robust nature of this technology and facilitate its adoption in future cable projects.

5. Summary

An open-loop cooling system designed for the HTS cable at Bixby Road has successfully cooled the cable for more than one year. Average heat load from the cable has been 1.6 kW, and the average overall heat load from the system has been 4.9 kW. Recent development by Praxair of a Stirling-type pulse tube cryocooler with a cooling capacity of approximately 1 kW at 77 K has made it feasible to deploy two pulse tube coolers at Bixby Road. These coolers will be installed in the fall of 2007. They will reduce the load on the open-loop system and their operation will demonstrate the applicability of pulse tube technology for the HTS cable market, where these cryocoolers can provide a reliable closed-loop refrigeration solution in a small footprint.
Figure 6. Three-dimensional model of the Bixby Road cooling system with pulse tube cryocoolers installed (left – compare with figure 1) and photograph of a cryocooler in its enclosure ready for installation at the site (right).

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References
[1] Stovall J P, Demko J A, Fisher P W, Gouge M J, Lue J W, Sinha U K, Armstrong J W, Hughey R L, Lindsay D and Tolbert J C 2001 IEEE Transactions on Applied Superconductivity 11 2467-72
Maguire J F, Yuan J, Schmidt F, Allais A, Bratt S, Hamber F and Welsh T E 2007 IEEE Transactions on Applied Superconductivity 17 2034-37
Weber C S, Lee R, Ringo S, Masuda T, Yumura H and Moscovic J 2007 IEEE Transactions on Applied Superconductivity 17 2038-42
Demko J A, Sowers I, James D R, Gouge M J, Lindsay D, Roden M, Tolbert J, Willén D, and Træholt C 2007 IEEE Transactions on Applied Superconductivity 17 2047-50
[2] Geschiere A, Willen D, Piga E, Barendregt P and Albaugh K 2007 Proc. 7th International Conference on Insulated Power Cables (Paris: Comité de JICABLE 07) pp 81-84
[3] Lynch N J, Minbiole B A and Royal J H 2007 IEEE Transactions on Applied Superconductivity 17 2467-72
[4] Potratz, S A, Abbott, T D, Albaugh, K B and Johnson, M C 2008 Stirling-type pulse tube cryocooler with 1 kW of refrigeration at 77 K Advances in Cryogenic Engineering vol 52, ed J G Weisend II (New York: American Institute of Physics) to be published