



The Development of High Temperature Superconducting (HTS) Power Cable Systems

The need to transmit power to meet an ever-increasing demand has been a challenge for decades. This article is focused on the cooling of high temperature superconducting (HTS) cables for power transmission and distribution. Many of the concepts presented can be applied to other HTS cable applications that might be found on ships and aircraft electrical power systems. A significant advantage of HTS cables is the reduction in the right of way required, compared to conventional overhead lines, as shown in Figure 1. This feature is especially important in urban areas where there is no room to use conventional overhead lines. In addition, electrical losses are greatly reduced since higher currents can be carried by superconductors in smaller cross-sections compared to conventional conductors. This has the advantage that the power transmitted can be at a lower voltage with superconductors for the same power, or significantly more power can be transmitted at the higher voltage due to the higher current-carrying capability.

High temperature superconductors are generally considered to be those conductors that have a critical temperature that can be cooled using liquid nitrogen, which typically falls in the range of 65 K to 90 K. Before the discovery of high temperature superconductivity, other cryogenic concepts were considered because of the advantages of low temperature power cables. The use of cryoresistive cables was an early solution discussed in Weedy and Rigby.[1] These systems relied on the decreased resistivity of conventional conductors, such as copper and aluminum, as temperatures were lowered. The designs for these cables would use liquid nitrogen as the coolant with pressures between 10 and 25 atmospheres and temperatures from 65 K to 100 K.

Superconducting power cables are generally found in three main arrangements, as

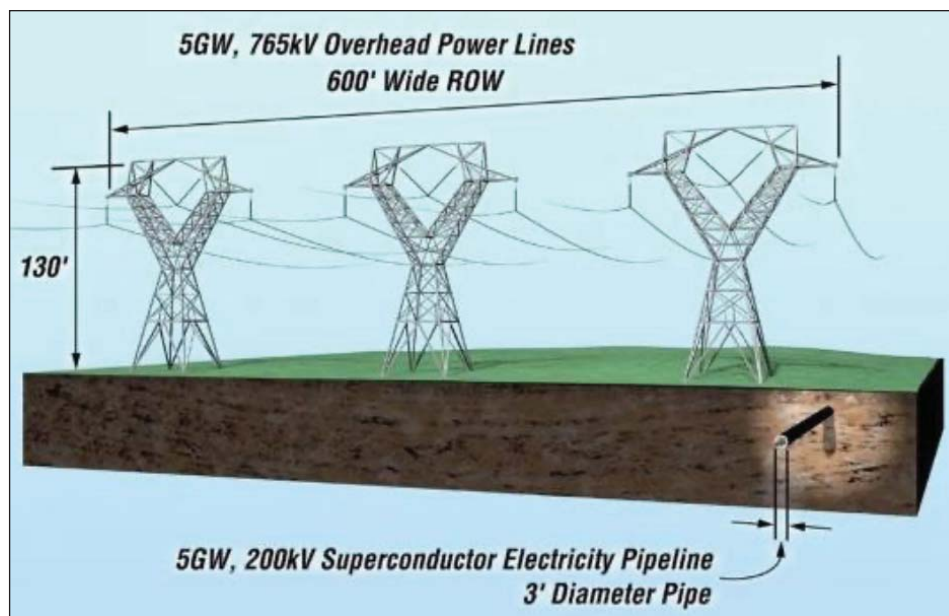


Figure 1: Comparison of conventional transmission installation with potential reduction of size for high temperature superconducting cable. Credit: DOE SPI Program

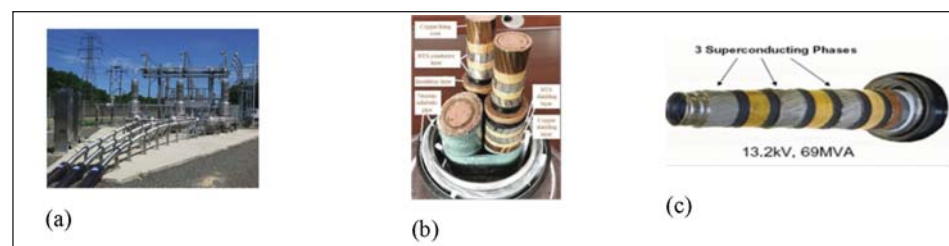


Figure 2: Typical HTS cable configurations. (a) Three separate coaxial HTS phases; (b) Cold-dielectric with an HTS shield triad layout; and (c) A concentric Triax™ design cable. Credit: McGuire, Zong and Demko^[5,7,2]

shown in Figure 2. Conventional and cryoresistive are only suited for the three separate co-axial phases, Figure 2a, and the triad configuration, Figure 2b. The triaxial cable was much more recently developed particularly for HTS cables.^[2] The triaxial cable configuration offers several advantages over the two other cable arrangements. First, the triaxial cable uses about half of the superconductor. The separate cable and triad require superconducting shield layers, which must carry the same current as the main conductor. The triaxial cable does not need the shield but only a conductor layer for current imbalance in the three-phase circuit.

When low temperature superconductors could be produced in long lengths and in large quantities, researchers focused their attention on superconducting power transmission cables. One notable early project was tested at Brookhaven National Laboratory (BNL).^[3] The BNL cable used a Nb₃Sn superconductor with a critical temperature $T_c \approx 16.6$ K. This required the use of supercritical helium as the coolant. The three-phase cable system was rated at 1000 MVA (330 MVA per phase) with 80 kV line-to-neutral or 138 kV three-phase rating with a design current of 4,000 A. The system, operated at BNL from 1982 to 1986,

had a length of 115 meters. There were two cables in the demonstration with an outer diameter of 5.85 cm. The cables were enclosed in a flexible cryostat with a 40-cm outer diameter. Cooling was in a counterflow arrangement, as shown in Figure 3. Supercritical helium leaving the refrigerator would be sent down the superconducting cables, and at the end there was an expansion engine that dropped the temperature of the helium, which flowed back through the cable cryostat to the refrigerator. BNL investigated the possibility of installing this in several locations.

Requirements of a HTS Cable System and Cryogenic System

HTS cables offer many advantages over conventional cables. There are requirements for the cryogenic system to meet. Since the preferred cooling is typically based on liquid nitrogen (except for special applications such as on electric-powered aircraft and ships), the operating temperature range is between 65 K and 80 K. The cable design considers the required critical current needed and, in turn, the ac loss associated with the conductor.

In many designs, liquid nitrogen is impregnated into the dielectric. The formation of bubbles would reduce the dielectric strength so the pressure must be maintained above the saturation pressure for all locations with high voltage. The cable cooling system would circulate liquid nitrogen under normal operating conditions, so sufficient refrigeration is required.

Cooling Configurations

There are two basic cooling arrangements for these systems. The first is a parallel flow where the coolant is circulated through the HTS cable in one direction. This lends itself to two possibilities for three-phase cables. The first sends coolant from the refrigerator through two phases and returns through the third, which is illustrated in Figure 4a. This is only applicable when there are three separate cables. The parallel flow arrangement in Figure 4b sends the cooling stream one way through the cable but uses an extra return line to bring the coolant back to the refrigerator. Weedy and Rigby suggest that the return line could be a second circuit used for redundancy.^[1] The

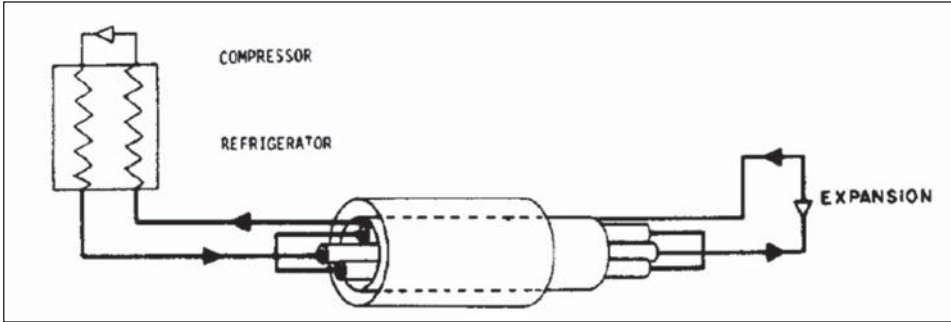


Figure 3: Counterflow cooling arrangement of the BNL low temperature superconducting cable. Credit: E.B. Forsyth and R.A. Thomas^[3]

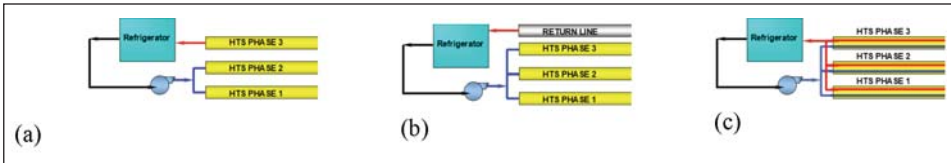


Figure 4: HTS cable cooling arrangements. Credit: Demko

Cable Layout	3-Separate Phases	Triad	Triaxial
Parallel flow	Yes	No	No
Parallel Flow Separate Return	Yes	Yes	Yes
Counterflow	Yes	Yes	Yes

Table 2: Possible cooling arrangements for HTS cable systems. Credit: Shu and Demko

Country	Year	Cable Type	Rating	Length	Manufacturer Site
US	2006	Three in one	34.5 kV/0.8 kA	350 m	SEI Albany
US	2006	Triaxial	13 kV/3 kA	200 m	Ultera Columbus
US	2008	Single core	138 kV/1.8 kA	600 m	Nexans Long Island
JP	2012	Three in one	66 kV/1.75 kA	250 m	SEI Yokohama
DE	2014	Triaxial	10 kV/2.3 kA	1000 m	Nexans Essen
KR	2011	Three in one	23 kV/1.25 kA	410 m	LS Cable Icheon
KR	2020	Three in one	23 kV/1.26 kA	1035 m	LS Cable Shingal
CN	2013	single core	35 kV/2 kA	50 m	SECRI Shanghai
CN	2023	Three in one	35KV/2,2KA	1200m	Shanghai

Table 3: Partial list of HTS AC cable projects.^[8] Credit: Shu and Demko

counterflow arrangement sends coolant out through the center of the cable and returns it over the outside of the cable (Figure 4c). In the case of the Triax™ it would be the most compact cooling arrangement. Table 2 shows cooling schemes suitable for different superconducting cable systems.

High Temperature Superconducting Power Transmission Cable Projects

Several HTS cable projects have investigated different aspects of these systems.

The three separate HTS cable phases have been demonstrated by Southwire Co. with a counterflow cooling scheme for a 30-meter-long demonstration rated at 12.4 kV, 1250-A, 60 Hz.^[4] Cooling was provided by a pressurized liquid nitrogen system operating between 70 K and 80 K using a counterflow cooling arrangement as shown in Figure 3c. The cable system provided 100% of the customer load, which was an early demonstration of the feasibility of this technology.

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A 600-meter-long demonstration project for the Long Island Power Authority (LIPA) was developed to operate at 138 kV, 2,400 amps, with a total power carrying capacity of 574 MVA.^[5] This also used three separate cables, but the cooling arrangement was as shown in Figure 3a, where coolant is sent down two phases and returned through the third phase.

The triad, or three-in-one HTS cable configuration, was used in the Albany Project which installed a HTS cable with a 350-meter length in 34.5 kV and 800 Arms in the real power grid of the National Grid Power Company.^[6] Recently, a 35-kV, kilometer-scale HTS cable demonstration project has been operating in Shanghai.^[7] Table 3 is a partial list of other HTS cable projects around the world that extended the length, voltage and current-carrying capacity of these cable systems.

Future of HTS Power Cables

The feasibility of using HTS power transmission and distribution cables has been demonstrated and offers advantages for certain applications over conventional cables. Reliability of the cryogenics and insulating vacuum are ongoing concerns that many have. The fault current capability of these cables is a feature not present with conventional conductors. Fault

current limiting was demonstrated on a 25-meter prototype for the Hydra Project.^[8] The 25-m HTS-FCL cable consisted of a three-phase (3- Φ) HTS Triax™ design with a cold dielectric between the phases. The HTS-FCL cable had an operational voltage of 13.8 kV phase-to-phase (7967 V phase-to-ground) and an operating current of 4,000 Arms per phase, which was the highest operating current of any HTS cable of that period. The 25-meter HTS-FCL cable was subjected to a series of cryogenic and electrical tests.

Another potential application of HTS cables would be for direct current (DC) applications, as discussed by Chowdhuri et al.^[9] Comparing alternating current (AC) and DC superconducting cables, the power-handling capability of an AC superconducting cable is limited by the stability limit of the power system; the DC superconducting cable has no such constraint.

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