



Superconductors in the transmission of electricity and networks[☆]

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ABSTRACT

A concise survey of superconducting power transmission (SPT) and associated topics is presented. After a brief background, which includes a summary of the probably now defunct low-temperature superconducting technology of the 1960s and 1970s, the article concentrates on the renaissance of interest in SPT with the advent of high-temperature superconductors (HTS) in the 1980s. AC and DC transmission and warm dielectric and cold dielectric conductors are discussed and some specific projects are outlined. State of the art is taken as current at the time of the Applied Superconductivity Conference 2004 [reported in IEEE Transactions in Applied Superconductivity 15 (2005)]. The benefits of HTS SPT are outlined, notably increased capacity and efficiency and its potential impact on energy conservation and the environment. The current state of development of HTS from first- to second-generation conductors is described, as is the possible role of magnesium diboride (MgB_2). Examples of future trends evolving worldwide are given and, finally, an assessment of the capability and funding for applied superconductivity in the UK is made.

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1. Background to superconducting power transmission

In a way, power transmission is the most obvious application of superconductivity as, on the face of it, losses, which can be as high as ~10%, are either virtually eliminated (for DC systems) or reduced significantly in AC systems. Also, and just as importantly, a dramatic increase in capacity can be achieved. The basic driver for reduced energy consumption, originally, was the OPEC oil embargo of 1973. After that scare, in subsequent years, an oil glut developed and the predicted growth in the demand for electricity did not happen. So, there was a loss of public interest in energy conservation. Now, however, several factors are emerging, which are causing a rethink on superconducting power transmission (SPT):

- High-temperature superconductors (HTS) make the technology more tractable.
- Oil prices are rising rapidly.
- Worries are emerging about security of energy supplies.
- Large power failures have occurred, e.g. 14 August 2003—the 'Northeast Blackout' in the USA and Canada.

More general environmental concerns are also becoming a preoccupation:

- global warming,
- CO₂ emissions,
- overhead power cables—adverse visual amenity/harmful radiation, and
- the expense and environmental dangers of conventional underground cables such as oil leakage.

What is clear is that of the order 3–5 times the power can be transmitted in a superconducting cable with the same, or less, loss than a conventional cable, which is an impressive increase in efficiency. The potential for retrofitting to increase capacity in growing, high-density urban environments is also clear (Malozemoff, 2006).

AC or DC? Superconductivity lends itself best to DC as, apart from refrigeration, losses can be almost totally eliminated as they are mainly ohmic. Indeed, for very long-distance transmission, DC may be a strong candidate. However, generation and end usage are almost exclusively AC and the costs of inversion and rectification can be high. In the medium term, it is likely that SPT will be employed in short runs where power density is important. Hence, the additional problems of AC for SPT must be addressed and solved.

2. Low-temperature superconductors (LTS)

A comprehensive review article by Forsyth (1993) gives a good account of the state of the art at the 'changeover' from LTS to HTS

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for SPT. Willis (2000) also gives a good summary with the benefit of a few more years' hindsight.

In short, several experimental systems were built and operated worldwide. Probably the most celebrated of these was the Brookhaven system, which was in place from 1975 to 1986 (Forsyth and Thomas, 1986). The favoured arrangement was a Nb_3Sn conductor refrigerated by supercritical helium, which has a low viscosity and lends itself to lengthy circuits with pumping stations well separated. Temperatures of around 7 K, average, are achieved. The critical temperature, T_c , of Nb_3Sn is 18 K, so a good operating margin is maintained, as would not be the case with the cheaper and easier to use NbTi with a T_c of 10 K. Another advantage of helium is the cryopumping that is achieved to keep the insulating vacuum 'hard'. Nevertheless, on balance, these low T_c cables were never likely to achieve widespread operational use and they never did.

3. High-temperature superconductors (HTS)

Since 1986 and the advent of HTS, a completely different complexion developed. Regardless of the tractability, or otherwise, of these new materials, the prospect of superconductivity at elevated temperatures opened up an entirely new perspective for power transmission. On paper, at least, several problems disappeared or diminished. The first and most obvious advantage was the fact that expensive helium, either liquid or supercritical, was no longer needed. With the discovery of the higher-temperature HTS materials such as bismuth strontium calcium copper oxide (BSCCO) and yttrium barium copper oxide (YBCO), the exciting prospect of liquid-nitrogen-cooled superconductors, with the implicit concomitant ease and economy of refrigeration, became a possibility. Moving out of the liquid helium regime, even by only 20 K or so, has an immediate benefit. Specific heats are such that dissipative processes, like that caused by reactive losses and the flux flow losses in superconductors, do not have the potentially catastrophic effects that they can have with LTS.

There has therefore been a sudden renaissance of interest in SPT using HTS only. It is unlikely that any other superconducting materials will feature now, with the exception of magnesium diboride, MgB_2 , which will be discussed briefly later. This is, of course, unless new materials emerge with properties better than those of what we currently think of as HTS materials.

On this tack, it is worth drawing attention to the fact that, at the time of writing, we are at an interesting stage of development of commercially available HTS conductors. For all practical purposes the only conductor for this application has been based on $Bi_2Sr_2Ca_2Cu_3O$ (BSCCO 2223). A powder-in-tube (PIT) technique is used to obtain filaments of BSCCO, often with the addition of Pb, in a Ag or Ag alloy matrix in a flat tape form. There are variants, e.g., with a reinforcing component, such as stainless steel, but the basic architecture is multiple filaments in a Ag matrix. Grasso (2003) gives a comprehensive account of the processing of these conductors. The main drawback is that these tapes are very expensive (around \$200/kA m, cf. ~\$15/kA m for Nb_3Sn or ~\$1.5/kA m for NbTi) and although their critical current densities have improved steadily, only niche applications of a high-value-added nature make their use economical. These have been dubbed 'first-generation' or 1G conductors. In recent years, a great deal of effort has gone into developing a second-generation (2G) conductor.

Second-generation conductors are based on the material $Y_1Ba_2Cu_3O$ (YBCO). Ironically, this found fame as the first 'liquid nitrogen' conductor but was rather displaced by BSCCO for quite some time. It transpires, however, that YBCO lends itself to good texturing, which eliminates the 'weak link' problem associated

with the granular materials, such as BSCCO. This texturing is achieved by epitaxial deposition of YBCO on a metal substrate, such as a nickel alloy, which may itself be textured, on which is deposited a buffer layer, or layers, which also may have texture imposed. Buffer materials are e.g. yttria stabilised zirconia (YSZ), cerium oxide (CeO_2) and lanthanum aluminate ($LaAlO_3$). Then a thin layer (~1 μm) of YBCO is applied by a variety of methods. A good account of the various techniques and materials is given on the MetOx website (metox.biz/tech_update). This coated conductor is becoming known as the second-generation or 2G conductor. One of the world's leading producers of HTS tape, American Superconductor (www.amsc.com/index.cfm) has just abandoned manufacture of 1G BSCCO and is now concentrating on 2G YBCO. Coated conductor, provided it can be reliably produced in commercial quantities, should have improved performance, especially at the higher temperatures, such as liquid nitrogen (77 K), and should be cheaper to produce.

There are basically two patterns of HTS power transmission cable: warm dielectric (WD) (Fig. 1) and cold dielectric (CD) (Fig. 2). These are described in several works, for instance, by Caracino et al. (2003). In WD cables, only the phase conductor is liquid nitrogen cooled. They can carry more than twice the power of a conventional cable with the same losses and are best suited for retrofitting existing pipe or duct systems. In CD cables, two concentric HTS conductors are used per phase: a central phase conductor and a coaxial 'return' or ground conductor. The insulation, or dielectric, is in the cryostat with the conductor and is also cooled with liquid nitrogen. The CD design offers rather better capacity and efficiency due to the return conductor, which shields the electromagnetic field from the phase conductor and cancels the perpendicular magnetic field component, thus reducing the superconducting AC losses and eliminating electromagnetic pollution. The tri-axial arrangement referred to in Table 2 is a variant of the CD design, with three concentric phase conductors instead of one.

The CD design will enable underground power cables with transmission capacities normally reserved for overhead lines.

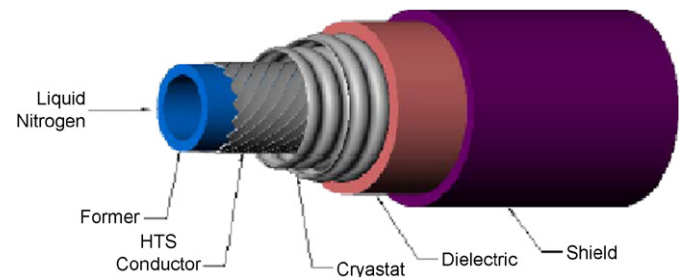


Fig. 1. Warm dielectric (courtesy of Ultera).

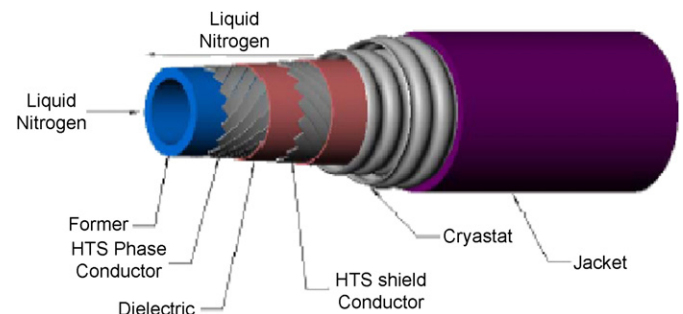


Fig. 2. Cold dielectric (courtesy of Ultera).

4. HTS projects

Since the early 1990s, there have been several HTS transmission projects worldwide. Some of these are shown in Table 1, which is based on Willis [3]. The most up-to-date projects are identified using the proceedings of the 2004 Applied Superconductivity Conference (Cho et al., 2005; Gouge et al., 2005; Maguire et al., 2005; Takahashi et al., 2005; Weber et al., 2005; Xin et al., 2005) as a benchmark. These are shown in Table 2.

The Southwire project (see Table 1) was quite successful and powered the company's manufacturing complex at Carrollton, Georgia, USA, and was in operation for some five years with '100% reliability and service' over three years at least (Lindsay and Willén, 2003). The NKT system in Denmark operated in a utility substation for two years. Now, based on their experience in these two projects, Southwire and NKT have formed Ultera, a company that features in the project to supply a 300 m cable at the Bixby substation in Ohio (see Table 2). The installation at the Frisbie substation in Detroit (Table 1) yielded valuable experience, but this ambitious project was not on the whole successful. Two of the phases developed cryo leaks, which would have meant continuous evacuation of the cryostats—an unsatisfactory mode of operation. One cable was kept in place in order to evaluate operation but the project was finally terminated in December 2004 (Electric Power Research Institute (EPRI): <http://amptest.epri.com/default.asp>).

Limited space precludes further detailed discussion of the projects in Table 2 but the references provide recommended reading.

5. Magnesium diboride (MgB₂)

It is worth briefly considering the possible impact of MgB₂ (Buzea and Yamashita, 2003). This has an appeal as it is cheap, light and, given further development, should not have the grain boundary problems associated with the cuprates. However, its critical temperature is only 39 K. For a reasonable operating margin, it needs to be used in the 20–30 K region. This is achievable with cryocoolers, but these may not be a practical proposition over long lengths of cable. Liquid hydrogen (20 K) would be the perfect refrigerant but modern safety standards mean that its use would be prohibited, although, given the benefits, perhaps looking into the safe use of hydrogen should be seriously considered. At present, it seems that MgB₂ is a possible candidate for localised power utility applications, such as fault current limiters and/or transformers and maybe even superconducting magnetic energy storage but not SPT.

5.1. The future

Now we have HTS materials, there is a growing confidence in the community that SPT will happen, certainly in the medium/

Table 1
HTS power transmission cable projects, 1992–2003

Institution	Location	Type of system	Parameters	Comments
Pirelli—EPRI SPI	USA, Italy	Flexible, warm dielectric	50 m, single-phase, 115 kV, 2 kA	Project completed
Pirelli—DOE SPI	USA	Flexible, warm dielectric	120 m, 3 × single phase, 24 kV, 2.4 kA	Installation at Frisbie substation, Detroit. Problems with refrigeration. Project ended 29,000 h Of operation over 5 years. First system to power a live load
Southwire Co.	USA	Flexible, cold dielectric	30 m, three-phase, 12.5 kV, 1.25 kA	U bend in system
Tokyo Electric Power Co.	Japan	Flexible, cold dielectric	100 m, three-phase, 66 kV, 1.25 kA	
Pirelli—EDF	France	Flexible, cold dielectric	50 m, three-phase, 225 kV, 2.6 kA	Scheduled for testing 2002
Pirelli—ENEL, Edison SpA	Italy	Flexible, cold dielectric	30 m, single-phase, 132 kV, 3 A	Scheduled for 4 years from 1999
NKT Denmark	Denmark	Flexible, warm dielectric	30 m, single-phase then three-phase, 36 kV, 2 kA	2-Year test—cryogenic problems. Project ended. First system in a power utility substation

Table 2
HTS power transmission projects

Institution	Location	Type of System	Parameters	Comments
Sumitomo, Superpower, BOC, Niagara-Mohawk Weber et al. (2005)	Albany, NY, USA	Tri-axial cold dielectric	34.5 kV, 800 A _{rms}	Initially BSCCO 2223 1G conductor to be replaced with YBCO 2G
Ultera, ORNL, American Electric Power Gouge et al. (2005)	Oakridge and Ohio, USA	Tri-axial cold dielectric	Target 200 m cable 13.2 kV, 3.0 kA _{rms}	Development cables tested at ORNL. 300 m cable to be installed at AEP's Bixby substation
Furukawa, CRIEPI, METI Takahashi et al. (2005)	Japan	Single-core cold dielectric	500 m 77 kV 1 KA	Longest energised cable so far. Three-dimensional layout
KERI and LG Cable Ltd Cho et al. (2005)	Korea	Single-core cold dielectric	30 m 23 kV, 50 MVA	Next step: three-phase cable
American Superconductor, Nexans, L'Aire Liquide, LIPA Maguire et al. (2005)	Long Island, NY, USA	Cold dielectric	660 m, 138 kV, 574 MVA	Due for energisation 2006 Underground section
Innopower Superconductor Cable Ltd and collaborators Xin et al. (2005)	China	3 × 33.5 m single-phase cables, warm dielectric	3 × 35 kV, 2 kA _{rms}	Third SPT cable installed in a power grid worldwide

long term. Also, other power utility and distribution infrastructures will become superconducting. Witness, for example, the amount of work being done on superconducting fault current limiters.

From a UK perspective, not much seems to be happening with SPT or associated localised utility devices. In the USA and elsewhere in the world, quite serious programmes are in train. The Electric Power Research Institute (EPRI) (2006) in the USA in its 2006 portfolio, Programme 122 sets out a programme that addresses not only SPT but also superconducting substation components with a view to an ‘all-superconducting substation, which would be 25% smaller, be more efficient, require reduced maintenance, offer up to three times the power handling capacity for the same area and provide improved performance such as intrinsic fault current limiting’.

In the UK, there is still considerable expertise in superconductivity and the associated cryogenic engineering. This is to be found in dozens of university institutes, some government facilities and in industry. After all, the world’s first and leading applied superconductivity company, Oxford Instruments, is British. It has a superconductor manufacturing division, albeit in the USA, which is turning its attention to HTS. There are several other companies with interests in cryo-technology and superconductivity. The British Cryogenics Council (www.bcryo.org.uk) attempts to be a focus for this activity. However, if the downturn in funding for applied superconductivity research in the UK, which has been apparent for the last ten years or so, is not soon reversed, much of the expertise will start to disappear.

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