

Electric power grid application requirements for superconductors

A.P. Malozemoff

Electric power grid applications impose many requirements on high-temperature superconductor (HTS) materials. In addition to a high superconductor transition temperature, these include all the parameters enabling a cost-effective, robust, and high-performance wire: high current-carrying capability in relevant ranges of field and temperature, flexibility and mechanical strength in a wire form, electrical and chemical stability, low ac loss, high wire uniformity, and low wire manufacturing cost with high reproducibility and yield. This daunting list explains why it has taken so long to bring HTS wires to where they are today—starting to be used in commercial power projects. The benefits of these wires are very significant: high efficiency and power density in an accessible temperature range, enabling high-capacity and easily installed cables, compact and powerful rotating machinery, and unique current-limiting functionality. However, the job is not done. Improved wire properties and reduced manufacturing costs of existing materials will further broaden the impact of this technology. Meanwhile the search for new materials—and for room-temperature superconductors—must continue, with more attention to thermal fluctuations, flux creep, and reduced anisotropy, which are critical to their application potential.

Introduction

Cuprates, fullerenes, MgB_2, pnictides . . . In recent decades, arguably no field has exploded with more exciting new materials discoveries than superconductivity, driven by humankind's thirst for knowledge (and fame) and also by the promise of revolutionary applications benefiting humanity.

To the extent that the potential applications are already recognized, awareness of their requirements is essential for focusing research and development efforts. A high superconductor critical temperature T_c is certainly one of these requirements, and the search for room-temperature superconductors has become a Holy Grail of materials research. Yet, by itself, higher T_c does not ensure successful application of a superconductor material. Indeed, NbTi, the most widely used superconductor today, has a T_c of only 9 K, while $YBa_2Cu_3O_7$ (YBCO), the most widely used high-temperature superconductor (HTS) to date,[1] has a T_c of only 90 K, compared to 135 K for an as-yet unused (and likely never to be used because of toxicity and poor current density) mercury cuprate.[2] A host of other requirements, including high critical current in a magnetic field, chemical stability and environmental inertness, mechanical properties, electrical and thermal stability, low ac loss, and—often most difficult of all—competitively low cost, are *all* necessary for economic success and broad impact.

Here, we review these requirements in the context of electric power grid applications,[3,4] where the opportunity for impact is huge in a world with burgeoning energy demands. Because of electricity's exceptional flexibility and efficiency, global electric energy use is growing inexorably, both in absolute magnitude and as a fraction of total energy use. This growth creates enormous challenges for global electric power grids: They need much higher capacity, particularly within the engines of this growth—the urban megalopolises proliferating around the world. In such urban centers, flexibility to introduce new power links is drastically limited by unacceptability of overhead power lines and by existing dense underground infrastructure. A second challenge to the grid arises from environmental issues, from waste heat and the growing threat of climate change. Addressing these issues will demand major efficiency improvements and development of sustainable energy resources, along with means to transmit huge amounts of power long distances from remote renewable generation sites with minimal energy loss. Grid stability is a third challenge, particularly from growing fault currents in urban environments. Fault currents are the large currents that flow in response to shorts in the grid, and they are increasing dangerously as ever more power sources are added to meet demand.

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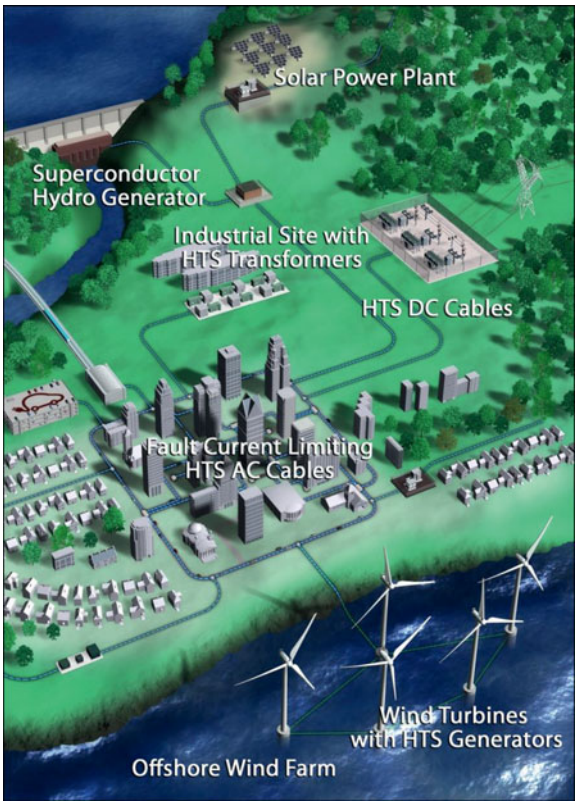


Figure 1. Schematic electric power grid with high-temperature superconductor (HTS) power equipment. (Image courtesy of American Superconductor.)

Superconductors offer solutions to these challenges, as suggested schematically in **Figure 1**. Their lossless current flow enables wires and cables with much higher power density than conventional copper, providing a solution to the urban capacity challenge as well as to transmitting power from distant renewable energy sources. Lossless current flow also offers increased efficiency in all grid components—cables, transformers, motors, generators, and current limiters. Power-dense superconductor generators allow cost-effective, offshore wind power, a major potential source of sustainable energy. And the fact that superconductors become resistive whenever the current exceeds a critical point provides an elegant means to limit fault currents.

For all of these applications, a robust, high-capacity and cost-effective HTS wire is essential. Two main types of HTS wire have been developed with existing cuprate HTS materials.[5] First-generation (1G) wires, fabricated using the BSCCO superconductors ($Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2Ca_2Cu_3O_{10}$) and a powder-in-tube deformation process similar to that for low-temperature superconductors, have a multifilamentary architecture within a silver matrix. Second-generation (2G) wires, also called coated conductors, use YBCO or its rare-earth analogs and have a thin-film HTS coating deposited epitaxially on a textured, tape-shaped template. Power applications set requirements on these wires and their constituent superconductor materials.[6] Here we review these requirements and identify directions for much-needed ongoing materials research.

Superconductor transition temperature T_c, upper critical field H_{c2}, and thermal effects

From an applications perspective, a superconductor transition temperature T_c as high as possible is always desirable because it enables higher-temperature operation, increasing refrigeration efficiency and reliability and thereby reducing system first costs and operating costs. An additional bonus is that the specific heat of all materials is much higher at the 77 K temperature of liquid nitrogen than at 4.2 K of liquid helium. The greater specific heat impedes thermal quenching of superconductors and makes HTS wire-based systems more stable.

Cuprate superconductors with $T_c \geq 90$ K have thus opened the door to large-scale power equipment—a major breakthrough. Discovery of a *practical* room-temperature superconductor (RTS) could allow superconductor technology to have even more impact, spreading throughout the grid and possibly even into the home. However, a practical RTS is a tall order. For one thing, superconductivity that persists to such high temperatures requires a much more powerful pairing mechanism than that in existing cuprates.[7] In addition, phase fluctuations grow with increasing temperature, suppressing the global phase coherence required for superconductivity even below the pairing temperature, as discussed in the Beasley article in this issue. And because the intrinsic critical current density J_{c0} scales to zero at T_c, T_c must be well above room temperature to retain adequate operating characteristics at room temperature.

Another issue for future higher T_c materials is achieving adequate tolerance to magnetic fields. The challenge here is not the classic problem of achieving a high enough superconductor upper critical field H_{c2}.[8] H_{c2} is very high in HTS materials because it scales inversely as the square of the coherence length ξ for the superconducting order parameter, which, in turn, scales inversely with critical temperature T_c.[9] Indeed, existing HTS materials such as the cuprates and pnictides have H_{c2} values of 50 T or higher, well above the highest field of dc magnets presently envisioned, and certainly above the 0–5 T range needed for power applications.

Rather, the problem is the so-called irreversibility line,[10] the empirically observed contour in the magnetic-field/temperature plane where the superconductor critical current density J_c drops to 0, as shown in **Figure 2**. Below this line, a nonzero supercurrent density is sustained by pinned or "irreversible" (though creeping) vortices (flux lines). Above the line, the pinning fails, and the material enters a vortex liquid phase with a normal, although low, resistivity. The position of the irreversibility line depends sensitively on vortex stiffness and therefore drops with increasing superconductor anisotropy. This result is well understood in terms of models based on vortex glass melting due to thermal excitation of vortices.[8]

Figure 2 shows that even though BSCCO-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$) has a higher T_c (110 K) than YBCO (90 K), its

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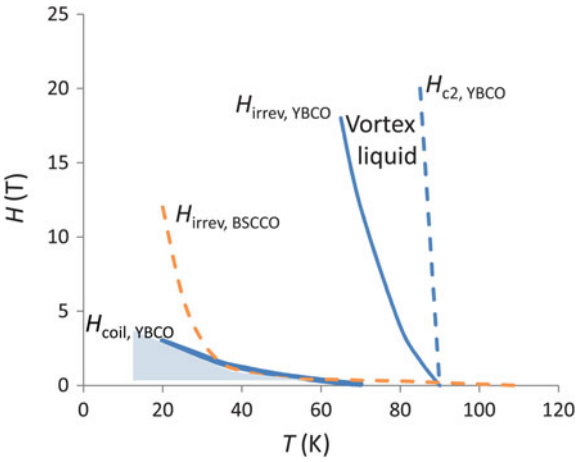


Figure 2. Field-temperature plots of the upper critical field H_{c2} and irreversibility line H_{irrev} of YBCO (yttrium barium copper oxide, in blue), and also, for comparison, the irreversibility line H_{irrev} of BSCCO ($Bi_2Sr_2Ca_2Cu_3O_{10}$, in brown). All fields are applied perpendicular to the cuprate *ab*-plane. The heavy dashed line, measured for an American Superconductor YBCO wire, indicates the field $H_{coil,YBCO}$ at which the wire achieves engineering critical-current density ≥20 kA/cm², an approximate minimum level for practical coil design for high-temperature superconductor rotating machines. The shaded region below H_{coil} is very limited, compared to the huge range between H_{coil} and H_{irrev}, where critical currents are too low. (Data for H_{c2} and H_{irrev} obtained from Reference 8.)

irreversibility line lies *below* that of YBCO ($YBa_2Cu_3O_7$), precluding applications in even modest fields above about 40 K. Indeed, for BSCCO, an intrinsic anisotropy parameter γ of 60 or higher has been reported, while that for YBCO is only around 6.[11,12] If the trend to higher anisotropy continues in new higher T_c materials, it will bode poorly for their usefulness in coil-based applications. These considerations highlight the importance of understanding the role of anisotropy in HTS materials. New materials with T_c in the same range as present cuprates, but with lower anisotropy, are likely to be more practical than higher T_c materials with higher anisotropy.

However, tolerance to high applied fields is not enough; a more challenging problem to enable practical applications is to achieve sufficient "engineering" critical current density J_e, the current density over the *entire* cross-section of the wire, including the substrate and stabilizer. For example, an approximate minimum J_e requirement for the kinds of coils used in large HTS rotating machinery is 20 kA/cm².

For a typical high-performance 2G YBCO wire produced by American Superconductor, the field-temperature range at which such a critical current density is achieved or exceeded is shown by the shading in Figure 2; it is limited by the dashed line labeled H_{coil} in the figure. In the enormous region above H_{coil} and below H_{irrev}, the critical current density, while nonzero, is nonetheless too low for useful applications. This is why HTS rotating machinery, even with YBCO, presently needs to operate in the 30–40 K range, rather than at 77 K.

Improving vortex (flux line) pinning that sustains current density and minimizing loss of current density at grain boundaries have therefore been critical areas for ongoing research. Much progress has already been made in the cuprates. However, an even more fundamental problem for the superconductor critical current density J_c, so far largely ignored in the search for higher-T_c materials, is flux creep. This slow vortex motion typically gives rise to a logarithmic decay of magnetization and of persistent critical current density J_c (as measured, for example, with a 1 μV/cm electric field criterion), suppressing it far below its value in the absence of flux creep, J_{c0}.[13] In cuprates over the middle of their temperature range, this suppression is almost a factor of five, making creep one of the largest factors controlling J_c.[14] Thus, finding ways to reduce flux creep is a great opportunity for improving performance for applications and deserves much more attention.

An approximate "interpolation" formula has been used to describe the relaxation with time t:[13]

$$J_c = J_{c0}/[1 + (\mu kT/U_0)ln(t/t_{eff})]^{1/\mu}, \quad (1)$$

where k is Boltzmann's constant, U_0 is the pinning energy of vortices that opposes flux creep, μ is an exponent of order 1 arising from vortex glass theory, and t_{eff} is an effective attempt time for a vortex or flux line to jump out of the pinning well.[13,15] In the low-temperature limit, this reduces to the classic Anderson-Kim flux creep formula, while in the high temperature limit, one finds a temperature-independent relaxation rate $S = dlnJ_c/dlnt = -1/\mu ln(t/t_{eff})$, which explains the temperature-independent plateau in S observed in many forms of YBCO.[15] In this region, $J_c/J_{c0} = [U_0/\mu kT\, ln(t/t_{eff})]^{1/\mu}$.

For a given application, the chosen operating temperature T will typically scale with T_c. Furthermore, in the simplest vortex-core-pinning model, $U_0 \propto H_c^2\xi^3$ is a superconductor condensation energy in a volume defined by the coherence length. Here H_c is the thermodynamic critical field, proportional to the energy gap Δ and thus to T_c, and the coherence length ξ scales inversely with T_c;[9] so one finds the vortex pinning energy U_0 scaling inversely with T_c. All in all, in the high-temperature limit of Equation 1, this simple argument gives J_c scaling inversely as the *square* of T_c, which is increasingly bad news for applications as T_c increases. More sophisticated collective pinning models for U_0 need to be examined as well; in such models, unless U_0 increases at least as fast as T_c, flux creep will progressively diminish J_c as T_c increases.

In addition to theory, studying flux creep in existing materials as a function of anisotropy could elucidate these phenomena, which are of critical importance for applications. Because weak coupling between adjacent CuO_2 planes in the highly anisotropic cuprates reduces vortex stiffness and thereby promotes flux creep, finding ways to decrease anisotropy while maintaining T_c could enable higher J_c and an increased useful H-T range. Indeed, the CuO chain layer electronically coupling adjacent to CuO_2 planes makes YBCO the least anisotropic and also the

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most useful of the cuprates. Can its coupling strength be even further enhanced?

Critical current density for underground power cables

High critical current density at the desired operating conditions is the single most important requirement for power applications. But requirements vary strongly with different applications and designs. For example, ac HTS underground power cables use tape-shaped conductors helically wound ("stranded") around a flexible cylindrical former, as shown in **Figure 3**. For a total operating current, these cables should use the minimum number of wires so as to reduce stranding costs and ac losses by limiting the number of winding layers to one or two. (The number of wires that can be accommodated in one layer is set by the former diameter and winding pitch.[16]) Given the relatively low surface fields generated by these cables and their operation in liquid nitrogen to minimize refrigeration costs, high current per wire width $I_{c,w}$ at 77 K in the presence of its self-field is desirable. Wires carrying 250 A/cm-width or higher have been used successfully in three-phase HTS cables carrying up to 2,000 A_{rms}.[4,16] For higher amperage (e.g., 4,000 A_{rms} cables are needed for some applications), a proportionally higher $I_{c,w}$ of 500 A/cm-width is needed. In contrast to coil applications (see later in text), the wire's engineering critical current density $J_e = I_{c,w}/d$, which is determined by the total wire thickness d, is less critical for cable applications, because the total current is more important than the density. In fact, a relatively thick stabilizer layer (100 μm or more) is advantageous to prevent buckling under bending strains.

To translate the $I_{c,w}$ requirement to a materials parameter such as the material's critical current density, J_c requires specifying the wire structure. For existing 1G HTS wires fabricated with a powder-in-tube technique, the BSCCO superconductor occupies up to 40% of the typically 200 μm-thick tape-shaped conductor. In this case, the $I_{c,w}$ = 500 A/cm-width requirement for 2-winding-layer 4000 A_{rms} cables translates to J_c = 62.5 kA/cm^2, a level successfully achieved with uniaxial texturing by 1G deformation processing.[17]



Figure 3. Cutaway of a typical underground power cable with high-temperature superconductor (HTS) tape-shaped wires wound helically around each of three cylindrical copper formers to form the three phases. Each phase conductor has two layers of HTS tapes, and around a dielectric layer, an additional one-layer shield of HTS tapes. (Image courtesy of LS Cable.)

For 2G HTS wires, adequate texturing to avoid grain boundary current limitations has required a thin epitaxially deposited film on a tape-shaped textured substrate. The corresponding J_c requirement to carry the same current per width in a 1 μm-thick film is 5 MA/cm^2, a level beyond the more typical 2–3 MA/cm^2 achieved with biaxial texturing in existing YBCO 2G wires at 77 K.[18] Higher thickness without significant loss of J_c through the thickness would enable meeting this requirement; this is an active area of ongoing work on YBCO superconductors.

DC cables have their own requirements. Here, the interest is to carry high power over long distances. One design recently proposed for a 5 GW cable[19] involves a bipolar configuration with two conductors carrying 12,500 A at ±200 kV, respectively. Such a huge current, if carried on helically wound tape-shaped conductors around a 25 mm diameter core, would create an azimuthal surface field of 0.2 T. In present HTS wires, such a field reduces the 77 K J_c by a factor of 2 or more, causing the required number of tapes and stranding layers to more than double, increasing cost substantially.[17,18] Further research on improved pinning to limit the 0.2 T field suppression of J_c at 77 K is therefore much needed.

What about round wires, which would facilitate compactly wound bundles for power cables or magnet applications? Among HTS cuprate materials, only $Bi_2SrCa_2Cu_2O_8$ (BSCCO-2212), with its liquid-phase reaction at a moderate temperature, has been successfully developed so far to yield a round-wire form.[4,17] Unfortunately, as a 1G wire without biaxial texturing, its 77 K J_c is not more than 50 kA/cm^2. Ideas for round YBCO wire have been proposed as well.[20] Compact bundled conductors also have high surface fields. For example, a 3,000 A bundle of round wires with J_c = 50 kA/cm^2, a 40% HTS fill factor, and a 2X safety factor would have a 0.65 cm diameter and a corresponding azimuthal surface field of about 0.2 T. For 77 K operation, this would require substantial improvement of in-field J_c. What is more, in this case, the field is no longer oriented along the material's more forgiving *ab*-plane, with serious consequences for ac losses (see text later). Using such a round wire in a 12,500 A dc cable with the previous J_c would require a bundle of about 1.3 cm in diameter with a 0.4 T surface field, further upping the J_c challenge. The requirements for such high current cables with round wires, however, can already be met at lower temperatures.

Critical current density for coils

AC coils are used in transformers and current limiters, and they can generate significant ac loss; because the high refrigeration costs to remove the excess heat are reduced at higher temperatures, ac coils of cuprate superconductors are operated typically only in a liquid-nitrogen environment. However, dc coils, such as the excitation coils on the rotors of synchronous rotating machinery, generate little loss, so the choice of operating temperature becomes a tradeoff between reduced refrigeration cost at higher temperature and increased J_c at lower

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temperature. HTS motors and generators are therefore typically operated conduction-cooled at 30–40 K.[21,22]

Fields produced by coils are proportional to their amp-turns; to minimize cost, the highest possible engineering critical-current density is required to increase the amperage per turn and minimize the length of wire required. Too much wire also makes the coil bulkier, neutralizing one of the main advantages of superconductor power equipment, namely high power density.

Successful operation of large dc excitation coils of HTS motors has been achieved using BSCCO-based (1G) wires with a 200 μm × 4 mm cross-section and critical currents of 250–300 A at operating temperatures in a maximum 2 T field perpendicular to the tape plane.[21,22] These wires were laminated on either side with 50-μm-thick supporting copper strips to improve stability. This corresponds to J_e = 21–25 kA/cm^2 or J_c = 78.1–93.75 kA/cm^2 in the tape-shaped powder-in-tube type of wire with stabilizer described previously, successfully achieved in the 30–40 K range. For YBCO-based (2G) HTS wires with a combined substrate, buffer, HTS and Ag passivation thickness of 80 μm, and two sandwiching copper stabilizer strips 50 μm thick plus 20 μm of solder, achieving the same engineering critical-current density would require J_c = 4.2–5 MA/cm^2 in a 1 μm-thick HTS layer. Again, such high J_c in a 2 T perpendicular field can only be achieved in the 30–40 K range with present YBCO wires, and further J_c enhancement is needed to extend the needed performance to higher temperatures. High field coils at 77 K are another Holy Grail, but so far, the highest fields achieved in a standalone 77 K HTS coil are only around 1 T.[23] However, at 4 K, HTS conductors can enable fields well above 30 T, higher than that of any metallic low-temperature superconductor.[23]

AC loss

The ac loss of a superconductor wire depends strongly on the environment in which it is used, including the peak amplitude I_p and frequency f of the current that it carries and the field H to which it is exposed. For example, in ac cables with helically wound tape-shaped 2G conductors, ac loss is dominated by the gaps between the neighboring conductors, and, to the extent that the wires do not conform perfectly to the circumference of the former they are wound around, by the geometry of the corners formed by neighboring wires.[24,25] For a fixed total operating current, superconductor hysteretic loss scales inversely as the square of J_c, so the highest possible J_c is desirable, although specific requirements depend strongly on the cable architecture.[24] Magnetic materials in some textured substrates for 2G HTS wires also contribute a ferromagnetic loss, a stimulus for further work to develop new nonmagnetic textured substrates.[26]

A different materials requirement emerges for wires subjected to strong ac magnetic fields, as in transformers or current limiters.[27] At low ac magnetic fields, the superconductor hysteretic loss scales as fB_p^3/J_c, where B_p is the peak amplitude of the ac magnetic induction. If B_p is high enough for flux to penetrate the superconductor completely, the hysteretic ac power loss per rms-ampere-meter is $P_{hysteretic} = afB_p$ (mks units), where a is the filament dimension perpendicular to the field.

We first consider a field oriented along the plane of an YBCO-based (2G) HTS wire, as would occur in the center of a solenoidal magnet constructed of a stack of pancake coils. With a modest peak ac field of 0.1 T_{rms}, and with a 1 μm HTS layer thickness and 60 Hz frequency, the predicted loss at operating temperature is only 0.008 mW/A_{rms}·m. However, with the field oriented perpendicular to a 0.4 cm wide wire, a condition occurring at the ends of a solenoid, the same ac field level gives a much higher at-temperature loss of 33.6 mW/A_{rms}·m. This corresponds to a required heat removal of over 1 W/A_{rms}·m at room temperature using a typical refrigerator coefficient of performance of 0.03. By comparison, copper operating at 200 A_{rms}/cm^2 at room temperature would give a resistive loss of only 34 mW/A_{rms}·m.

It has been known for a century that current losses in windings can be reduced by filamentizing the wire and transposing the filaments with one another along the wire length, but this is exceedingly difficult to do in a thin film. This sets a major challenge for HTS transformer applications, since one of the main drivers for HTS transformers is reduced ac loss vis-à-vis conventional copper transformers. For current limiters, a bifilar winding scheme has been shown to reduce inductance and stray fields, and thereby reduce ac loss to an acceptable level.[28] Very fine round filaments stranded into transposed bundles with a controlled degree of electrical coupling between the filaments are a path to low-loss ac wire for magnets, but this has so far been very difficult to achieve in HTS materials. Round-wire, filamentized BSCCO-2212 is so far the closest approach to this goal, but its high anisotropy and low irreversibility field reduce its application range in multi-Tesla fields to less than 20 K.[23]

Mechanical, electrical, and chemical stability

Wires for cable applications must withstand high mechanical tensions and bending strains during stranding and, even more critically, the tensions arising from thermal contraction when the cable is cooled to operating temperature. First-generation HTS wires with a soft silver matrix, when unreinforced, have tensile yield stresses below 100 MPa at 77 K and are barely viable for applications.[12] Lamination with thin stainless steel strips or other reinforcement can bring the tensile yield stress to as high as 400 MPa at 77 K, meeting typical cable application requirements.[29] Second-generation HTS wires generally have higher yield stresses thanks to their stronger substrates, such as nickel-tungsten alloy, Hastelloy, or stainless steel. But even here, especially for Ni-5 at% W with a 77 K yield stress of 250 MPa, lamination with reinforcing strips can be important.[30] With sufficiently thin wires with thickness, typically in the range of 200–400 μm, tensile bending strains up to 0.5%, and extraordinarily large compressive bending strains over 1.2%, can be accommodated,[31] which means that the wire can be bent around a radius of curvature as small as 4–8 cm.

Similar requirements arise in coil-based applications, plus a special requirement on tensile strains perpendicular to the tape plane (i.e., along the material's c-axis), which arise from differential contraction between the coil and its support. The latter issue has been solved in laminated conductors by the

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use of solder fillets at wire edges.[32] Thus, except for the case of ultrahigh-rotation-rate (e.g., 15,000 rpm) generators that apply unusually high centrifugal forces, current HTS wires with lamination have met the mechanical requirements for power applications. New materials will have to find similar solutions.

Electrical stability against quenching of superconductors at a "hot spot" or defect, or even due to a mechanical disturbance, has been a major issue in developing practical low-temperature superconductor wires.[27] With HTS, this problem is significantly reduced because of the vastly higher heat capacity, although if a quench nonetheless occurs in an HTS coil, a low quench propagation velocity complicates designing an adequate coil-protection scheme.[33] In BSCCO (1G) HTS wire, the superconductor filaments are embedded in a stabilizing pure-Ag matrix, and in YBCO (2G) wire, appropriate laminates or electrodeposits provide a high-conductivity stabilizer.[34,35] Wires properly tested against "dropouts" (i.e., defect locations with significantly lowered I_c) have been found to be adequately stable in the liquid-nitrogen environment of power cables. The somewhat lower temperature (30–40 K) conduction-cooled environment of coils for rotating machines presents a greater stability challenge, but here too, existing wires with a high-conductivity stabilizer, either Ag or Cu, have been found to be adequately stable, as in the successful full load test of a 36.5 MW ship propulsion motor based on BSCCO (1G) HTS.[21] In summary, conductor stability requirements have been met by forming composites of high-conductivity metals with the HTS material. New materials will require similar solutions.

Contamination and toxicity are more serious issues in power applications than in semiconductor electronics because of larger amounts of material involved and the risk of vaporization by the high power unleashed in a short circuit event. Superconductors for the power grid should therefore avoid toxic elements, including Tl, Hg, and Pb that are present in several cuprate families, and arsenic in the pnictides. In Europe Pb is now explicitly controlled by the European Restriction of Hazardous Substances Directive of 2003.

Any superconductor must also avoid contamination during synthesis, and contamination and decomposition during its lifetime. For cuprate superconductors, this is challenging since most elements in the periodic table poison the superconductors if allowed to diffuse into the lattice. Fortunately, the noble metals Ag, Au, and Pd are inert and do not diffuse, even at high synthesis temperatures (typically 700–800°C). Because of its relatively low (though still high!) cost compared to Au and Pd, Ag is almost universally used as the interface for electrical contacts or for forming a composite with desirable mechanical and electrical properties.

A variety of oxides can also form a stable template for the cuprates, such as rare-earth oxides and barium zirconate. Since epitaxial growth is key to 2G HTS wires, approximate lattice matching with the template oxides is also important. The tendency of YBCO to lose oxygen when directly exposed to air, even at room temperature, has been thwarted by passivating it with a thin Ag layer. Any new material needs to achieve similar chemical stability.

Cost

Perhaps the most difficult requirement for any superconductor in power applications is low cost.[6,36] Since the amount of wire required is controlled largely by the current capacity, there is a direct tradeoff of cost with current, as reflected in the widely relevant cost-performance metric: dollars per kiloAmp-meter ($/kA·m). Here, the number of Amperes used for normalization is the current in full operation, which in cable applications is typically half the critical current. The economic viability of a given superconductor application is of course determined by the cost of *all* of its components, including, in the cable case for example, not just the superconductor wire but also the former, dielectric, refrigeration and control systems, supporting materials, installation, and operation. The HTS advantage in avoiding tearing up city streets by retrofitting slender high-capacity cables through existing conduits makes HTS cables an attractive solution in many cases even with present-day wire costs.

Nevertheless, a useful cost-performance benchmark for HTS can be set by comparison with copper. Material prices have varied drastically in recent years, with the spot copper price surging from $1.3/lb in January 2009 to $4.4/lb in January 2011. Assuming 100 A/cm^2 maximum operating-current density in copper in underground cables, these prices, even ignoring the costs of processing to wire, correspond to 26 and 87 $/kA·m, only somewhat below the range of 150–300 $/kA·m, where HTS wire typically sells today. The present prices of HTS wires are low enough for some applications, although reducing the HTS cost differential compared to copper is part of the ongoing effort to make HTS

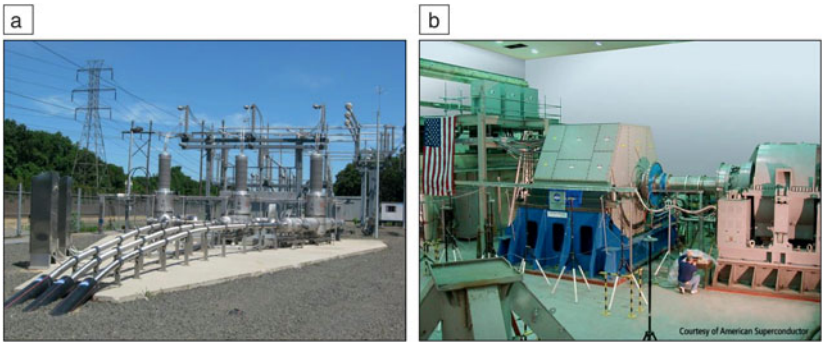


Figure 4. (a) World's first transmission-voltage high temperature superconductor (HTS) power cable system, installed in the Long Island Power Authority's (LIPA) commercial power grid in April 2008. At full capacity, the 138 kV system is capable of carrying 574 MW of power and powering 300,000 homes. The three cables shown can carry as much power as all the overhead lines on the far left. (b) World's first 36.5 MW (49,000 horsepower) HTS ship propulsion motor, manufactured by American Superconductor (AMSC) and successfully tested at the U.S. Navy's Integrated Power System Land-Based Test Site in Philadelphia. Using AMSC's HTS wire, the motor is one-third the size and weight of a conventional 36.5 MW marine motor. (Images courtesy of American Superconductor.)

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power equipment more broadly competitive. Any new material will face a similar challenge.

The superconductor wire cost includes materials and processing costs. While commercial manufacturers do not disclose the latter, some interesting conclusions emerge from materials costs alone. Like copper prices, silver prices have surged in the last two years, from $10/oz. in late 2008 up to $30/oz. in late 2010. For the 1G powder-in-tube wires using a silver matrix constituting 60% of a 200 μm × 4 mm cross-section, silver cost per length ranges from 1.78 to 5.33 $/m. With a wire carrying 100 A (under operating conditions, about half of the highest critical currents available in commercial BSCCO 1G wires today), this corresponds to 17.8–53.3 $/kA·m. Thus the silver cost alone represents a significant fraction of the copper benchmark, undermining the long-term commercial viability of 1G HTS wire, whether tape or round. By comparison, even though YBCO 2G wires have a very thin layer of silver, nickel is by far their dominant materials component. Given that nickel's price has risen from just below $5/lb in January 2009 to $12/lb in January 2011, a 0.4-cm-wide wire with a 75-μm-thick nickel substrate would have a corresponding nickel cost of only 2.9 to 7 cents/m, a significant cost advantage vis-à-vis 1G wire.

Conclusion

It is a truism that for a material to work successfully in a given application, it must meet *all* application requirements. And these are many, making materials development for applications a challenging process, usually requiring decades and causing a large assortment of initially promising materials to be winnowed down to a very few.

Nowhere has this been more true than in the field of high-temperature cuprate superconductors. First discovered in 1986 and now celebrating their 25th anniversary, they have proliferated into a smorgasbord of hundreds of compounds. But only a very few—YBCO, BSCCO-2212, and BSCCO-2223—have made their way into commercial wires and significant electric power grid and magnet demonstrations, such as the HTS cable and motors based on BSCCO-2223 1G wires (**Figure 4**). While the long-term winners have yet to be determined, YBCO in the form of 2G wire looks to be the most promising today and is already impacting the first commercial applications. It deserves strong ongoing research and development to further enhance its capabilities to meet even the most advanced requirements described in this article. At the same time, the search for a room-temperature superconductor is also important, a great challenge to human ingenuity and imagination. But more attention needs to be paid to flux creep and thermal effects, which will be major obstacles in turning such a material, even if discovered, into a practical material for the electric power grid.

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