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The Potential of Superconductivity

High-temperature superconductors can replace aging grids with greatly enhanced capacity.

This country's energy infrastructure has undergone dramatic improvements in efficiency over the past three decades, particularly since the "energy crises" of the 1970s. However, despite these overall gains in efficiency, there is still new potential for energy savings, particularly in the area of generation, transmission and distribution of electricity. Furthermore, electricity consumers are demanding higher and higher levels of reliability in their power supplies as the nation's commerce is increasingly conducted online.

Heading into the 21st century, it is important to remember that many of today's methods of generating and delivering power date back nearly to the late 19th and early 20th centuries when Thomas Edison was still alive and designing electrical equipment. For example, the circuit breakers installed by Detroit Edison in the 1930s are still in operation, despite demand growth that is taxing the performance of these breakers. Experts agree that our nation's electricity infrastructure is overdue for modernization and/or replacement. The onset of electric utility restructuring and market competition around the country only highlight the antiquated nature of much electrical equipment still used by most utilities today.

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In addition, our nation's electricity grid is strained to the limit, with the result that blackouts and brownouts are becoming increasingly common during peak demand periods throughout the country. This also means that increased generation of electricity from renewable sources of energy such as wind, solar, geothermal and biomass might not be able to be used economically due to their inaccessibility to the grid. It is infeasible to transmit such "green" power over long distances because of line losses.

High-temperature superconductivity (HTS) technology, however, can replace present grid segments with greatly enhanced capacity, thereby giving the grid more flexibility and reliability, along with the ability to accept cleaner new, renewable generation. Increased efficiency in the generation, transmission, distribution and storage of electricity through the use of HTS would also mean that less electricity will need to be generated in the first place. Other HTS applications, such as motors, transformers and fault current limiters, can help modernize and revamp our nation's electricity infrastructure for the 21st century and beyond. The energy and environmental benefits of HTS will be significant and beneficial, with full implementation of this technology projected to offset the emissions of 40 medium-sized conventional generation plants.

DOE's Program

The U.S. Department of Energy's (DOE) Superconductivity for Electric Systems Program plays the leading role in coordinating partnerships between government and private industry in advancing superconductivity research, development, and commercialization. DOE's Superconductivity Partnership Initiative (SPI) is designed to accelerate HTS products into the marketplace with financial incentives for the development of superconducting products. SPI features a 50% cost-share with industry, aimed at field-testing advanced power products. Each SPI project team contains not only a potential manufacturer, but also involves a future product user (such as an electric utility), a superconducting component supplier, and, often, a Department of Energy (DOE) national laboratory.

A second major DOE thrust in the superconductivity program is aimed exclusively at the development of second generation wire, with a goal of achieving low cost, high performance HTS wires that will operate acceptably at temperatures near 77 degrees Kelvin (the temperature of liquid nitrogen at 1 atmosphere pressure) and in strong magnetic fields. Six industrial consortia are involved in this initiative.

The DOE superconductivity program addresses key technical areas where improvements are needed to achieve commercialization. The two major technological goals are: (1) solving the difficult problem of manufacturing electrical wires from the family of brittle ceramic superconducting materials and (2) creating designs of super efficient electrical systems such as motors, transmission cables, generators, transformers, and current limiters that use these wires. Several key HTS applications are profiled below.

Motors. Large motors convert 30 percent of all U.S. electrical energy generated, and 70% of these motors are well suited to utilize HTS technology. Experts estimate the worldwide market for HTS motors greater that 1000 hp to be $300 million per year.

HTS motors are cryogenically cooled, "super" efficient synchronous machines with HTS field windings. The primary applications of these devices will be large motors (greater than 1000 hp) used for pump, fan and compressor drives for utility and industrial markets. Applications requiring continuous operation will provide the best environment for those motors. HTS motors may increase machine efficiency beyond 98%, reducing losses by as much as 50% compared to conventional motors, producing energy savings, reduced pollution per unit of energy produced, and lower life cycle costs.

The cost drivers for HTS motors are, as with virtually all HTS products, refrigeration and wire costs. The SPI team developing electric motors is lead by Rockwell Automation/Reliance Electric and includes American Superconductor, Centerior Energy, Air Products and Chemicals and Sandia National Laboratories.

Field tests in an appropriate user environment are necessary for market development and commercialization to take place. Motors of 1000 hp and 5000 hp are being developed for this purpose. Operation of the 5000 hp motor is scheduled for August of 2001.

Fault Current Controller (Limiter). A *current controller* is designed to react to and reduce unanticipated power disturbances in the utility grid, preventing loss of power to consumers or damage to utility grid equipment. The primary application of the HTS current controller will be for the reduction of fault current. The device will perform as a fast sub-cycle breaker when installed at strategic locations in the transmission and distribution systems, especially for electric utilities and large energy users in high growth, high density areas.

Utilities will benefit tremendously from this application. It provides increased safety, reliability, and power quality; it is compatible with existing protection devices; its maximum allowed current is adjustable, which means greater system flexibility; and it defers the need for transmission and distribution system upgrades, which reduces required capital investment. The HTS current controller allows enhanced operating capacity of utility systems. Conventional copper-based current limiters (i.e., line reactors) can cause voltage instability in the electrical system by adding reactance (a resistance to the flow of current) to the system. This forces the utility to add capacitance to the system to counterbalance the reactive element. No capacitive correction is needed with a superconducting current controller, since it has no reactance and is passive during non-fault conditions. Utilities can reduce or eliminate the cost of upgrades to circuit breakers and fuses by installing HTS current controllers. Fault current levels on a typical transformer can be as high as 10 to 20 times the steady state current. One conventional solution to limiting fault current is the use of higher rated circuit breakers and power fuses. Large capital costs are incurred not only to upgrade the circuit breaker, but also the entire substation buswork. By design, the superconducting current controller will limit fault current to three to five times the amount of steady state current, reduce standby energy losses, and provide improved flexibility.

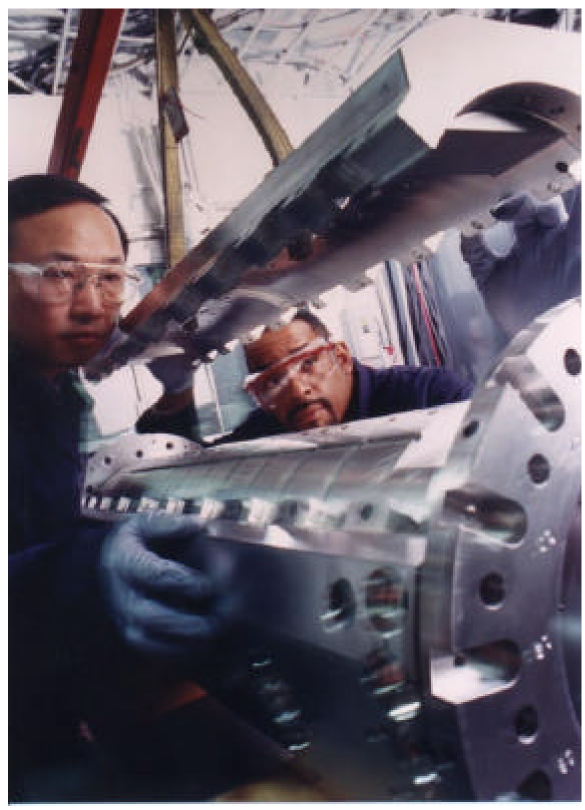

Figure 1. Assembly of prototype 1000 hp motor incorporating HTS rotor coils [photo by American Superconductor Corp.]

HTS fault current limiter (FCL) efforts are being pursued aggressively around the world, while the SPI Fault Current Limiter team consists of General Atomics, Southern California Edison, Intermagnetics General Corporation, and Los Alamos National Laboratory.

A 2.4 kV current controller was successfully tested in September 1995 at a Southern California Edison substation, while in 1999 a 15 kV device was tested by the same utility. After field testing of this 15 kV unit, engineers identified areas where the current controller needed to be modified or redesigned. These modifications will take place at Los Alamos National Laboratory before reinstallation at the utility's substation.

The cost of current controllers is still prohibitively high, with the cost drivers being the superconducting material (wires) and the refrigeration systems. Utility acceptance will take considerable time, and therefore, demonstrations of the capabilities of this type of new equipment will be essential to marketplace success.

Transformers. Compact, quiet, lightweight and superefficient HTS transformers will primarily be used at substations within the utility grid. Environmentally friendly and oil-free, they will be particularly useful where transformers previously could not be sited, such as in high-density urban areas or inside buildings.

Utilities will derive many benefits from HTS transformers. In addition to significantly greater efficiency, they are also considerably smaller and lighter. They do not require cooling oil like conventional transformers, which eliminates fire and environmental hazards. HTS transformers, therefore, can safely operate almost anywhere. Additionally, with a smaller footprint, HTS transformers can deliver more power per unit volume in existing substations. They are also capable of handling overload without loss of equipment life.

The ongoing growth in urban power density is a primary driver of the need for medium-sized power transformers to become smaller, lighter, and free of fire hazards. HTS transformers have all of these attributes. The existing U.S. transformer market for 10–100 MVA devices is $260 million, and $120 million for devices greater than 100 MVA.

Two SPI teams are pursuing transformer development technology in parallel. One team consists of Waukesha Electric, Intermagnetics General Corporation, Rochester Gas and Electric, Oak Ridge National Laboratory, and Rensselaer Polytechnic Institute. The second team consists of ABB Power T&D Company, Inc., American Superconductor, Air Products and Chemicals, Inc., American Electric Power Co., Southern California Edison, and Los Alamos National Laboratory.

A 1 MVA HTS transformer was tested by Waukesha in 1997. A 5/10MVA, 26.4 kV/4.16 kV HTS transformer is now being designed to power the Waukesha electric systems plant. A 30 MVA design is also being completed. Component models are being tested, with installation expected to occur in 2001.

Once again, commercial success of this application will be driven by the cost, and the main cost factors are the cost of the HTS materials and the refrigeration system.

ABB has previously designed, built, and operated an HTS transformer on a 630 kVA three-phase utility grid in Geneva, Switzerland. The present team intends to build, test, and install in utility service a 10MVA, 69kV/16kV HTS transformer to be operational in the June 2001 time period. A 100 MVA design will also be carried out. The

Figure 2. Southwire Company's Carrollton, GA, manufacturing facility, where three 100-foot HTS power distribution cables provide electricity to three of the company's manufacturing plants. [photo by Southwire Company].

latter product will be cooled with liquid nitrogen, will be substantially lighter than conventional transformers, and will require no oil.

Wire Cost and Technology. Scientists at U.S. companies and six national laboratories are jointly exploiting research breakthroughs that promise unprecedented current-carrying capabilities in HTS wires. However, the main requirement for commercial electric power applications is that the wires be flexible and strong enough to carry large current in a magnetic field. The HTS wire fabrication technology still needs improvement to meet cost and performance requirements for widespread application. Overcoming this technology barrier is a main focus of the Second Generation Wire Development effort within the overall DOE program.

One team, led by 3M Corp. in partnership with Southwire Company, Los Alamos National Laboratory, and Oak Ridge National Laboratory, is exploring the feasibility of the materials and processes to improve the current-carrying capacity of short wire samples (one meter in length), and scaling up the length toward levels required for commercial applications. The team is investigating such issues as substrate fabrication, buffer layer alignment, superconductor deposition, and mechanical properties in their effort to achieve cost-effective long-length HTS wires made from $YBa_2Cu_3O_x$.

Industry experts project that the entire market in the United States, Japan and Europe for superconductor products and services will reach $122 billion by the year 2020. Large end users of electricity, such as paper mills and steelmakers, as well as companies with a need for steady and reliable power, such as semiconductor manufacturers, will especially benefit from the increase in capacity and reliable nature of this HTS wire.

Refrigeration. SPI principals have identified refrigeration design and cost as one of the two crucial drivers in the decision process to commercialize superconducting products. Efficiency can vary dramatically based on the needed operating temperature of the superconducting device addressed, and efficiency relates directly to cost of operation.

A tradeoff occurs in refrigeration design. Increased efficiency requires more complex and complicated systems with designs intent upon minimizing losses. This raises first cost, but lowers operating costs. Conversely, a lower first cost, simpler refrigeration system will probably require more expensive operation and maintenance costs. In either case, SPI principals indicate that the refrigeration technology for these products must be improved.

Currently, HTS devices are expected to be cooled with closed-loop cryocoolers, which are a mature, highly reliable, and relatively low cost technology already in use worldwide in thousands of MRI machines in hospitals.

Cable. HTS transmission cables will be used for power transmission and distribution, in place of today's conventional cables. Current estimates are that approximately 2,200 miles of existing underground cables are installed in the United States, many of them nearing the end of their service life. HTS cable, carrying three to five times more power than conventional cable, can meet increasing power demands in urban areas via retrofit applications. Power transmission in underground HTS cables can substitute for overhead transmission lines when environmental and other concerns prohibit overhead installation. Exceptionally low losses will enhance overall system efficiency, increase flexibility, and reduce electricity costs.

One of the two SPI teams participating in cable efforts is led by Southwire Company and includes Argonne National Laboratory, Oak Ridge National Laboratory, EURUS Technologies, Georgia Transmission, Southern Company, and Southern California Edison. This team installed a 30 meter three-phase cable to supply power to two of its manufacturing plants and its machinery division. This is the world's first industrial field test of a superconducting cable system. The cable will carry a 20 MVA peak load, enough to power the city of Carrollton, Georgia (Southwire's corporate headquarters). As the need for transmission and distribution increases in a U.S. atmosphere of urban transmission constraints and enhanced environmental awareness, a technology that can carry great quantities of electric power in confined, underground spaces will become more and more desirable.

The key to market readiness of HTS cables may be utility readiness to accept the vagaries of a new technology that will have a highly visible effect on overall utility service reliability. The price drivers are the refrigeration system and the basic cost of the HTS materials. The minimum time to commercial sales is estimated to be at least 3 to 5 years.

In another project—the Detroit Edison Cable Pilot Project—within approximately a year, 18,000 pounds of conventional copper cable will be replaced with a few hundred pounds of superconducting metal tape housed in a cable system chilled with liquid nitrogen. These three HTS cables will supply enough electricity for a city of 16,000 people. A key SPI initiative, this project is sponsored by DOE and led by Pirelli Cables, with team participants Los Alamos National Laboratory, American Superconductor Corporation, the Electric

Power Research Institute, Lotepro and Detroit Edison.

Generators. About two percent of the electricity provided by a conventional generator is lost during generation in the form of heat caused by resistance and other factors. However, HTS generators lose no power due to resistance, making them 99.5% efficient, enabling a large savings in electricity and energy costs. Most activity in superconducting generators is currently taking place in Japan, where Kansai Electric has successfully tested a 70,000 kW-class low temperature superconducting generation system at the utility's power plant in Osaka.

Summary. With its efficient, loss-free generation, transmission and distribution of electricity, the promise of high temperature superconductivity is rapidly being realized in laboratories and through field tests around the country, and indeed the world. Once its feasibility and tremendous potential has been demonstrated in actual field conditions (such as in the Detroit Edison pilot project), it appears increasingly likely that utilities and transmission companies around the country will seek to gain a competitive edge by using this promising new technology.

HTS will also provide potential PR opportunities for utilities as well, since the greater efficiencies made possible by HTS would allow utilities to concentrate on increasing the "greenness" of their electricity—and thus its appeal to the growing "green market." Without HTS, even "green power" still has some environmental taint caused by line losses and inefficiencies. Additionally, the vastly increased transmission capacity afforded by HTS means that many controversial new rights-of-way through sensitive wilderness areas or dense urban centers will not need to be sought once this technology is commercialized.

The clean, nearly loss-free potential of HTS is an excellent match for clean and inexhaustible renewable energy technologies. The economic opportunities should also be huge, as companies race to incorporate HTS into their grids, much as the telecommunications industry is doing with fiber optics. Identified by the Electric Power Research Institute as a key electricity technology of the 21st century, HTS can help make an energy-efficient and renewable energy future more feasible and affordable for our country and the world in the next century.