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INTRODUCTION

High temperature superconductor (HTS) materials, discovered in the 1986, are now commercially available worldwide. Two categories of applications have emerged: (1) low-field applications at 77 K achieved with liquid nitrogen, and (2) high-field applications at >25 K achieved with cryogenic refrigerators. The promise of low-cost HTS conductors coupled with reasonably priced refrigeration systems has encouraged application of this technology to a variety of magnets and power equipment. Many prototypes have been constructed for electric power applications such as motors and generators, transformers, power transmission cables, fault current limiters, Maglev trains, and magnets for applied physics research.

According to the US Department of Energy, motors account for three-quarters of all energy consumed by the domestic manufacturing sector and use over half of the total electric energy generated in America. Large electric motors, those greater than 1000 horsepower, consume over a third of the total generated electric energy, and three-quarters of these motors are suited to utilize HTS technology. With some minor exceptions, nearly all cruise ships today employ electrical propulsion, and many other types of commercial vessels and warships are adopting marine motors as their primary source of motive power.

Applications of High Temperature Superconductors to Electric Power Equipment,
by Swarn Singh Kalsi

Superconducting technologies could also benefit ancillary equipment for smooth operation of the electric grid; examples of such applications are superconducting electromagnetic energy storage (SMES) and fault current limiters (FCLs). In addition to improving system efficiency, superconductors reduce size and weight of equipment. Transformers are the prime candidates for employment of the HTS technology because they are the most widely used equipment in an electric grid. Most of the power is generated as AC at relatively low voltages and is utilized at even lower voltages, but the bulk of power is transmitted from points of generation toward points of consumption at very high voltages. Transformers convert electric power from one voltage level to another.

The electric grid inevitably experiences extreme natural events and faults. Fault current limiters, such as fuses, are employed to limit the fault current and allow an electric grid to keep operating. However, fuses require manual replacement after a fault. The HTS fault current limiters are self-acting and resetting devices that allow the grid to recover quickly following a fault.

Power cable built with HTS wire could carry several times more power than the conventional copper cables of similar physical size. The space freed by use of HTS cable is available for enhancing power transmission or other applications.

Large electrical magnets are employed for a variety of industrial, research, and military applications. The manufacture of such magnets with HTS materials is looking attractive. The HTS magnets possess attractive features such as smaller size and weight, higher efficiency, higher fields, better stability, longer life, and easier cooling.

The four main HTS materials are BSCCO-2223, YBCO-123, BSCCO-2212, and MgB_2. However, only BSCCO-2223 and YBCO-123 wires capable of operation in the temperature range of 20 to 70 K have achieved widespread application for manufacturing practical electric power equipment. The YBCO-123 in form of coated conductors has also advanced significantly to provide current density capability suitable for application in practical devices. Roebel cables, made from the coated conductors, could carry currents in kA range with minimal losses. The BSCCO-2212 wire has also been utilized for building insert magnets for operation at 4 K in high background fields. This material in form of bulk rods is also employed for building fault current limiters operating in liquid nitrogen baths. MgB_2 conductors are also being fabricated, but their current-carrying capability is still lower than the other HTS materials.

Despite higher field and higher operating temperature capabilities than the low-temperature superconductor (LTS) materials (NbTi and Nb_3Sn), the MRI, accelerator, and fusion magnet communities have not adopted the HTS materials so far. These applications employing LTS materials are purely DC magnets operating at around 4 K and are very sensitive to even a small thermal energy injection that could raise local temperature sufficiently to drive the magnet into quench. Very low heat capacity of materials at low temperatures (around 4 K) causes this phenomenon. Then again, materials in HTS conductors operating at about 30 K have heat capacity hundreds of times higher than that at 4 K. Thus any local energy injection causes a much smaller temperature rise. HTS materials also transition slowly to their normal state because of a low *N*-value.* These two factors, enable the HTS magnet to operate successfully in the presence of significant local heating.

HTS materials have proved to be successful in many applications where LTS materials have been unsuccessful especially for industrial applications. HTS conductors operating at liquid nitrogen temperature are employed for building power cables, fault current limiters (FCL), and transformers for applications in AC electric grid. Numerous large projects in these areas have been successfully built. The HTS conductors are also used for building high field DC coils for excitation poles of large AC synchronous motors and generators. These coils are employed on the rotor and are cooled with a stationary refrigerator employing thermo-siphon or gaseous helium loops. The cooling is accomplished with an interface gas like He or neon, which transports thermal load from coils to the stationary refrigerator. A few examples of many large motors and generators successfully built include 8-MVA and 12-MVAR reactive (MVAR) synchronous condensers, the 4-MW, two-pole generator for marine application, 5-MW and 36.5-MW high-torque ship propulsion motors, and 1000-hp and 5000-hp industrial motors.

The largest potential market for HTS conductors lies in the electric power arena and involves power transmission cables, high-power industrial and ship propulsion motors, utility generators, synchronous condensers, fault current limiters, and transformers. The Northeast blackout of August 14, 2003, provided incentive to accelerate development of such power equipment utilizing HTS wires.

This book reviews key properties of HTS materials and their cooling systems and discusses their applications in power devices such as

*N is the exponent of the V-I curve for the HTS wire.

rotating machines, transformers, power cables, fault current limiters, Maglev trains, and magnet systems. Example device designs are included to allow the reader to size a device for his/her application. Ample references are provided for exploring a given application in details.

So far the high cost of HTS materials has inhibited commercial adoptation of HTS power devices. Estimates of the maximum acceptable price for different applications range from $1 to $100 per kiloampmeter, where kiloamp (kA) refers to the operating current level. In particular, NbTi wire typically sells for $1/kAm but is limited to operation in the liquid helium temperature range. HTS conductors operating at 20 to 77 K are expected to be economical for some applications in the $10 to $100/kAm range. In power equipment, copper wires typically operate in the range of $15 to $25/kAm; this sets a benchmark for superconducting wire. Thus HTS materials must compete against copper in electric power technology where cost pressures are very significant.

Many synchronous machines prototypes (both generator and motor) were developed worldwide between 1995 and 2010. These machines included slow-speed machines (100—200 RPM) for ship propulsion applications and high-speed machines (1800 and 3600 RPM). Since most of these prototype machines employed expensive BSCCO-2223 HTS material, it was not possible to transition them into products. However, currently available YBCO-123 coated conductors promise low-cost and higher current capability. This is encouraging renewed interest in developing synchronous generators for central power stations and wind farms.

Underground power transmission HTS cables have been amply demonstrated with both BSCCO-2223 and YBCO-123 coated conductors. Many prototypes are currently in operation throughout the world at voltage ratings ranging from 11 to 138 kV. Although these prototypes demonstrate benefits of the HTS technology for the users, high capital cost and reliability issues are inhibiting their adoption.

Today a number of fault current limiter (FCL) projects are underway. Most employ YBCO-123 in tape or bulk form. Some prototypes are already operating in electric grids. FCLs are solving electric utility problems that are difficult to address with currently available technologies. However, the success of FCLs will be determined by the capital cost and reliability considerations.

Many power transformers were also prototyped between 1995 and 2005 all over the world. Most employed BSCCO-2223, which was not found suitable for this application because of high AC losses. New projects are being initiated now with YBCO-123 coated conductors, as these promise to reduce losses in the acceptable range. These conductors are being considered as wide tapes or in form of Roebel cables. Although the HTS transformers offer higher efficiency and lower weight, their future will be determined by the economic viability and reliability in operation.

To encourage future customers to adopt the HTS technology, it is essential that standards be developed on par with those for similar conventional equipment. HTS equipment must satisfy all requirements imposed by current industry standards (CIGRE, IEEE, NEMA, VAMAS, etc.) on the existing conventional equipment. If a certain requirement cannot be met by HTS equipment, then alternate arrangements must be made to ensure that the performance and reliability of new equipment are on par with currently available conventional equipment. The standards activity must be started now. Presently, IEEE and CIGRE are initiating standards development activity for HTS rotating machines and FCLs.

Although many niche applications of the HTS technology are feasible, only a widespread adoption will lower the cost of HTS materials and the cooling systems. This is a typical chicken-and-egg problem. Most applications require lower cost HTS conductors and cooling systems, but developers require more demand (orders) for reducing cost. By the 2020s some economic products are likely to emerge.