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Review of high power density superconducting generators: Present state and prospects for incorporating YBCO windings

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Abstract

This work focuses on the development of high power density generators for airborne applications by bridging the chasm between generator and high temperature superconducting (HTS) wire developmental efforts. Benefits of HTS power generation include improved efficiency, thermal management reduction, improved power handling, reduced life cycle costs, and size and weight reduction. Superconducting generator development from the 1970s is outlined, and the basic types of ac synchronous generators are described. The benefits of HTS conductors in general and HTS coated conductors in particular are discussed. Critical issues for the employment of HTS coated conductors are then considered and recommendations made for enhancements to the HTS coated conductor for implementation in the more advanced superconducting power generators.

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1. Background

1.1. The need and niche for high power density generators

A variety of future military systems will depend on high electrical power input at the multimegawatt level. As is typical for airborne, seaborne, and ground-mobile platforms, the power generation subsystems must often be packaged in a limited space and within strict weight limits. Conventional generators that provide high electrical power have been developed and optimized over the past several decades, but these generators cannot provide the multimegawatt levels of power necessary for advanced mobile or airborne military systems without paying a significant penalty in size, weight, and efficiency. Efficiency, thermal management, and fatigue life are typically sacrificed as conventional generators are given high rotational speeds to reduce their size and weight while maintaining the high power output. Thermal management dictates that as the required power increases to megawatt levels, simple scaling of conventional airborne power generators is not a plausible solution.

The development of more efficient airborne generators is of critical importance. While the systems that use this power are being intensely developed, the greater power needed to make these systems function is often assumed. Only proactive efforts on novel power systems such as HTS generators will address these concerns. Below we will review some of the past technical accomplishments in the development of LTS-based generators. Several fundamental roadblocks prevented widespread incorporation of these machines. HTS conductors can allow these limits to be circumvented, however, HTS conductors may have their own set of difficulties to be addressed. In order to enable the successful development of high power density generators and their widespread usage, both a critical review of LTS-based generators and an assessment of relevant issues for HTS conductors are needed. We will start by outlining

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the application niche for near-term military and governmental use of such generators, which may occur before large-scale commercial uses are feasible.

Perhaps the earliest use for the superconducting technologies will be non-lethal weapons. Future military applications will likely broaden the range of situations in which military force can be used as a first strike option with non-lethal technologies. One specific technology being developed for such situations is Active Denial Technology (ADT) [1]. ADT is a non-lethal directed energy weapon (DEW) which employs high power electromagnetic radiation. To make this system airborne will require the benefits of superconducting generators [2]. Also, the required gyrotron magnet is made with LTS. If this magnet could be replaced with HTS conductor operating at 60–77 K (as opposed to 4.2 K) it would result in a significant reduction in weight, size, and electrical power requirements of the associated cryocooler.

There are other applications for the US Air Force, Navy, and Army requiring large amounts of power. The US Air Force is also considering airborne DEW such as the Airborne Tactical Laser (ATL). Even chemically driven directed energy weapons such as the ATL will require greater electrical power to pump the chemicals through the laser. Similarly, the Army has a technological need for compact, lightweight power systems for DEW applications on mobile platforms such as Ground Tactical Lasers. Development is also ongoing with both homopolar and synchronous superconducting motors to drive the US Navy's future all-electric ship [3]. HTS wire technology can be used in many of the system components for these military applications such as motors, power generators, transformers, power converters/inductors, primary power cabling, and high field magnets.

Technologies such as electromagnetic launch or railguns require pulsed power [4], but often overlooked is the fact that the required average power of these application may extend into the megawatt range. This would require a continuous electrical power generation system to charge the energy storage system, whether capacitor banks, pulse forming networks, etc. [5] as an alternative to pulsed alternators. Command and control operations are also demanding more power such as with the E-10A Multi-Mission Command and Control aircraft (MC2A). The MC2A would be capable of serving as an intelligence, surveillance and reconnaissance platform with a broader range of capabilities in a single package.

Another potential application is in the arena of Homeland Defense. It is clear that commercial airports, power utility generation, and power distribution grids are vulnerable to terrorist attack. Solutions to counter these possible attacks would make use of small multimegawatt turbogenerators which can be permanently located or rapidly deployed to these areas in the event of an attack. In the case of airports, a highly mobile superconducting power generation system could be employed to power advanced protective measures. For the transmission grid, these mobile high power generators can be deployed to critical nodes if power is disrupted. The system could simply be an aeroderivative turboshaft engine coupled to a HTS generator to produce the required megawatts of power; the system could be contained in a trailer for transport to its needed location.

In this work, we will aim to discuss the nature of this newer class of superconducting generators that is being developed to meet the needs outlined above and some of the requirements for incorporation of the HTS coated conductor. The intent is to establish a bridge between the development of these two technologies. HTS generators will use superconducting windings which maintain high efficiency (and thus lessen thermal management requirements) and at the same time more critically reduce the machine size and weight. This paper will focus in particular on the superconducting ac synchronous generator work especially relevant to the US Air Force, and the roadblocks and possibilities associated with HTS conductor use.

1.2. The need for superconducting windings

The primary commercial application of superconducting generators will be in power utility facilities, either as new acquisitions or as retrofitted generators. Benefits of commercial HTS generators include energy savings, reduced pollution per unit of energy produced, lower life-cycle costs, enhanced grid stability, and reduced capital cost and installation expenses. The greatest incentives for the development of HTS generators are in the commercial sector as opposed to the military due to the significantly larger market for power utility applications. However, governmental agencies are expected to be a driver in the development of this technology in the near term, because they represent an enabling technology for some military systems. Below we review some of the specific reasons for using superconducting wire, especially HTS.

1.2.1. Increased efficiency and thermal management

The lack of dc resistance in superconducting wire virtually eliminates ohmic heating in the field windings of generators. Superconducting generators can increase machine efficiency beyond 99%, reducing losses by as much as 50% when compared to conventional generators. For airborne generators, the increase in efficiency is even larger, by several percent. In fact, efficiency per se is not the main benefit here, more important is the fact that the improved efficiency significantly lessens the thermal management burden. At the lower overall power levels currently used in airborne applications today, the amount of waste heat does not pose a great problem. However, as power levels are increased to the megawatt level, the thermal management load becomes a non-neglible factor in the design of airborne generators. For example, if 5 MW of power is produced at 85% efficiency, then 750 kW of heat must be either dumped off-board the aircraft or absorbed by the fuel.

1.2.2. Size and weight reduction

Initial commercial, HTS-based generators are expected to be a third or less of the overall volume of their conventional equivalents and one-half or less of their weight. Indeed, superconducting synchronous motors have already demonstrated reductions of this level [6]. This reduction factor included the cryogenic refrigeration system and no special effort was taken to reduce its size. Less superconducting wire is needed compared to copper in order to obtain the same magnetic field. Furthermore, the magnetic fields produced by the superconductor winding are high enough that no iron is needed to direct the field lines (depending on the particular generator configuration), which also means that the rotor-produced fields are not limited by the saturation characteristics of iron. This lack of iron also eliminates the losses experienced in the armature teeth. Superconducting generators built without iron in the rotor or stator and are referred to as "air core" designs; this fact also contributes to the weight savings versus conventional copper wound generators. Such designs are of particular interest to the US Air Force, although usage of iron, if minimized, can still pose a viable solution. Incorporating these elements into the design and increasing the rotor speeds to greater than 10,000 rpm, as is typical in airborne generators, a total reduction of $\sim$80% is achievable in size and weight for the generator itself.

1.2.3. Enhanced power grid performance

Another benefit of superconducting generators is related to its incorporation into the overall power grid. These advantages are more applicable for usages at bases and installations as opposed to mobile systems. The associated advantages include steady state and transient stability, such as a greater tolerance of negative sequence fields, an improved reactive power capability, and a potential increase of up to $\sim$30% in the power transfer limits of the transmission system [7]. One particular generator design had a low synchronous reactance, although the transient and subtransient reactances are close to conventional values [8]. For HTS generators, a reduction in the amount of spinning reserve (unused but rotating generating capacity) is needed to ensure a stable overall power system [9]. It is also expected that an HTS generator has the capability of being significantly overexcited to permit power factor correction without adding synchronous reactors or capacitors to the power system [9].

1.2.4. Low life-cycle costs

If the reliability and maintenance of a superconducting generator are comparable to present systems, it is expected that a reduction in life-cycle costs can be possible. Since superconducting generators are smaller and lighter than their conventional counterparts with the same power rating, capital costs, shipping fees, and installation expenses can potentially be less, especially as the power output of the generator is increased. Superconducting generators can also offer a longer operating lifetime than conventional machines since conventional windings generally experience insulation degradation resulting from thermal aging. Cryogenic applications can retard this degradation and the insulation of HTS generator field windings should last longer and not require the standard rewinding maintenance. An added environmental benefit of using superconducting wire for generators is a reduction in oil consumption [7].

2. Introduction to superconducting synchronous generators

2.1. Components

Superconducting ac synchronous generators work by electromagnetic induction; all rotating electric machines provide power based on Faraday's law. The ac voltages generated are the result of an induced electromotive force resulting from time varying magnetic fields. In a generator, this is accomplished by motion between the armature winding and the magnetic field windings (rotor coils or excitation coils). Either the armature windings are rotated within the field produced by the excitation coils or vice versa. When the excitation coils are rotated, they are referred to as the rotor; the stationary armature is then called the stator. Superconducting generators usually incorporate the superconducting wire into the rotor field windings while retaining a non-cryogenic armature which employs standard copper windings.

One approach for creating a power subsystem is to configure a prime power unit (PPU) with a combustion turbine engine that drives directly (without a gear box) a high speed superconducting synchronous generator. The cryogenic sections of the synchronous generator would be cooled by an efficient and reliable mechanical refrigerator. Fig. 1 shows a typical power system layout for a superconducting generator mated to a gas turbine. The Power Management and Distribution (PMAD) scheme is dependent on the load. For example, a high voltage load might have a transformer as part of the PMAD. On the other hand, a low voltage load PMAD might use dc-to-dc power converters. The synchronous superconducting generator can be divided into three major subcomponents: the rotor, the stator, and the cooling system (Fig. 2). The cooling system is generally stationary requiring cryogenic cooling lines connecting to the spinning rotor. On airborne generators with high rpm, the HTS coils in the rotor will experience large centrifugal forces.

2.2. Hybrid vs all-cryogenic designs

Basic synchronous superconducting generators can be sub-classified into two primary types. The first is the classic (or hybrid) superconducting generator. This is the primary design that has been used to-date in which only the rotor windings use superconductors. The stator has a conventional design using copper windings except for the elimination of the iron. In the rotor windings, the superconductor will generally experience a dc field, thus ac losses are kept

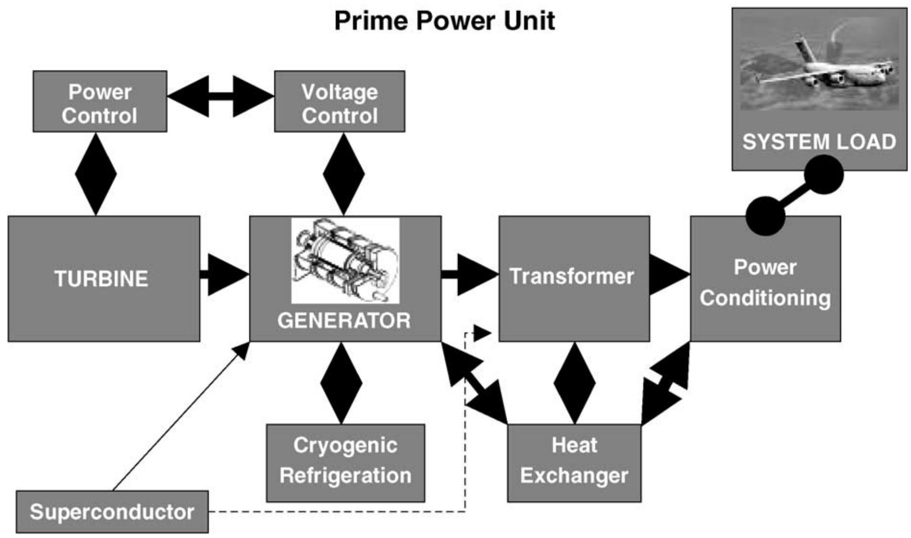

Fig. 1. Cryogenic power system block diagram.

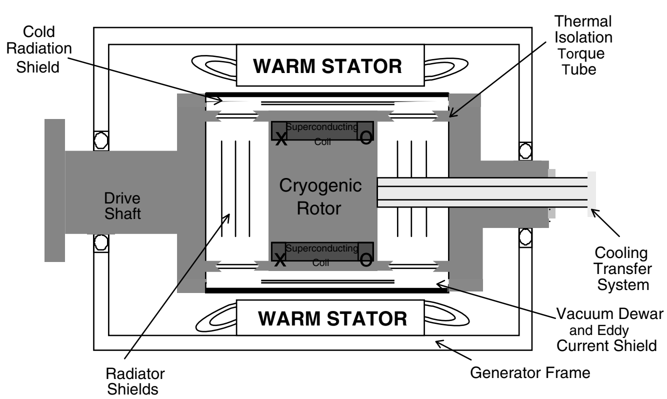

Fig. 2. Basics of a classic superconducting generator.

to a minimum and largely due to asynchronous feed back. Efficiencies of the structure are high since the superconductor has zero dc resistance. However, there are issues associated with isolating the rotating cryogenic vessel from the room temperature stator and the required cryogenic cooling connections to the spinning rotor.

The other class of superconducting generators is the all-cryogenic or fully superconducting generator. In this case, both the rotor and stator windings are made of superconducting material and the entire generator resides in a cryogenic jacket. The armature windings will experience significant ac losses due to the rotating magnetic fields of the rotor. These ac losses will include hysteretic losses in the superconductor, normal metal effects such as eddy currents, ferromagnetic substrate contributions, and coupling current losses. Successful incorporation of HTS conductor into the armature will require the additional development of an ac-tolerant YBCO coated conductor that will sufficiently minimize these effects. Until such time, hybrid superconducting generators will be the workhorse for superconducting power systems.

Ultimately, however, an all-cryogenic design is the ideal for lightweight superconducting generators. This type of superconducting generator has a much simpler design and potential for high reliability. The weight improvement resulting from ac-tolerant YBCO stator coils is perhaps not the dominant factor in that the real benefits of the all-cryogenic machine will be in manufacturability, reliability, and affordability in comparison with other types of lightweight generators. The all-cryogenic approach can potentially double the power density of the classical superconducting generator—one with HTS rotor only.

3. Development of superconducting generators to date

In establishing new programs for the development of superconducting generators, it is important to understand what progress has already been made. Below we focus on the development history of ac synchronous generators, but parallel efforts for the ac synchronous motor, although not provided here, have also been considerable. Of course the basic design approach for motors is similar, excepting that motors convert electrical power into mechanical motion whereas generators do the opposite. We will also not address the efforts in superconducting dc homopolar generator/motor development (refer instead, for example, to [3,10]).

3.1. Initial prototype LTS work (late 1960s–1970s)

One of the first US Air Force generator designs was an all-cryogenic, superconducting system that incorporated both a superconducting field winding and a superconducting armature winding. This was a 50 kW synchronous machine designed by Dynatech in 1967 [11]. Although not successful, testing demonstrated the very real issue of ac losses in a superconducting armature winding. Later machines used superconductors in the field windings exclusively. In this case, a vacuum space must be used to separate the cryogenic field windings and room temperature stator.

Several small synchronous superconducting alternators with stationary superconducting field windings and conventional rotating armature windings were being constructed by various groups. Examples of these occurred in the late 1960s and early 1970s throughout the world: an 8 kVA machine in the United States (AVCO), a l00 kVA machine in Russia, a 21 kVA machine in Germany, and a 30 kVA machine in Japan (Fuji Electric) [12]. During the same time period, development of generators with rotating field windings and stationary armature windings—more typical of later development efforts—were constructed and tested. Early efforts at MIT included a 45 kVA device and later a 2 MVA machine. A 1 MVA machine was also built in the former Soviet Union.

During this time, a two-pole, 60 Hz, 5 MVA machine with a rotating dewar assembly was built and tested by Westinghouse [13]. Additionally, the US Air Force contracted Westinghouse to build a 5 MVA, 400 Hz machine (Fig. 3) [14]. The 12,000 rpm superconducting four-pole rotor designed for this machine was constructed and tested in 1974 (without an armature), sustaining 240 A at 12,000 rpm—a speed appropriate for airborne applications and consistent with 5.32 MVA operation. The alternator development program used NbTi in the rotor windings, necessitating 4.2 K operation. Even so, the electromagnetic shield on the rotor was considered the most significant problem of the superconducting alternator, which caused excessive heating in the shield due to load-induced varying fields. This suggested that future designs have separate thermal and electromagnetic shields to avoid the heating problem [15]. The combination of poor cooling and high losses placed strict design constraints on the superconductor specifications.

Fig. 3. Superconducting NbTi-based 5 MW generator, circa 1974, resulting from an Air Force contract with Westinghouse.

3.2. The second wave of LTS (late 1970s–1990s)

The high rotational speeds achieved in the Westinghouse (US Air Force) program demonstrated that superconducting field windings were capable of handling large centrifugal loads. This implied that much larger machine diameters were, in fact, feasible at the lower tip speeds used for 1000 MVA commercial applications. In 1975, the Electric Power Research Institute (EPRI) contracted Westinghouse and General Electric to perform conceptual design studies for both a 300 MVA and a 1200 MVA superconducting generator for implementation by the power utility industry. This led to a follow-on program with Westinghouse on the 300 MVA design, which ran until 1981 [7]. General Electric also built and tested a 20 MVA superconducting generator in 1980 using in-house funding.

Working together, Mitsubishi Electric and Fuji Electric, under the support of the Ministry of International Trade and Industry (MITI) of the Japanese Government, constructed and successfully tested a 6.25 MVA, two pole, 60 Hz, 3600 rpm superconducting generator in 1977 [16]. This was the first machine with rotating superconducting field windings constructed in Japan. The field coils were wound with monolithic NbTi wire and consisted of nine separately impregnated coils for each pole. These companies went on to develop another superconducting machine as a synchronous condenser with capacity of 30 MVA in both leading and lagging phases, completed in 1982 [16]. Hitachi also constructed a superconducting generator with a 50 MVA capacity. The rotor was completed in 1982 and tested with a small stator [16]. A 1000 MVA generator was subsequently designed by Hitachi based on the 50 MVA machine [17].

International development (e.g., in France, China, and Italy) of superconducting generators was also occurring in the late 1970s to early 1980s [18–20]. At the Technical University of Munich in Germany, a 320 kVA test generator of the rotating-armature type was built to investigate the dynamic performance of superconducting generators. It was put in service in 1979 and operated in the 1980s during the course of a long-range test program. Kraftwerk Union and Siemens of Germany also ran an extensive program to develop superconducting turbogenerators of commercial size for the electric utility industry [21]. The Former Soviet Union tested a 20 MVA turbogenerator in 1983 [22].

During the 1980s, General Electric built another 20 MVA superconducting generator for the US Air Force (Fig. 4). The field windings were made using Nb/Ti, with plans to retrofit with Nb_3Sn wire. During this time (1985), Massachusetts Institute of Technology built a 10 MVA alternator [23]. However, most LTS-based generator efforts were curtailed with the discovery of HTS; research focused on the HTS conductor development due to the prospect of higher operating temperatures, especially liquid nitrogen operation. During the late 1980s, the MIT alternator program was probably the only significant US

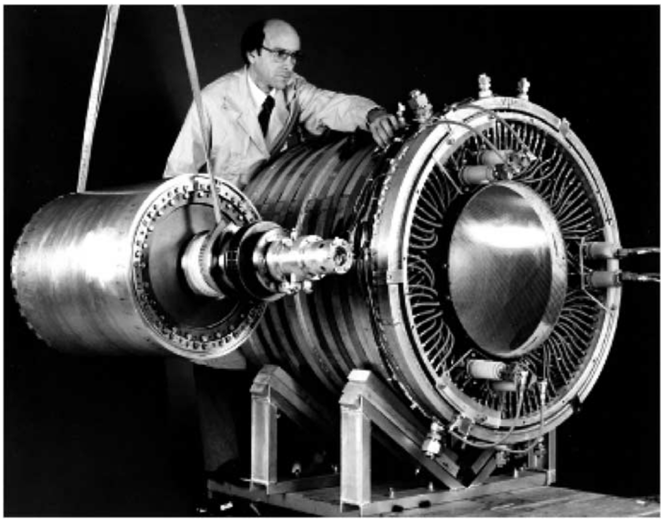

Fig. 4. General Electric 20 MW LTS generator (1981).

dedicated effort other than the GE generator for the US Air Force for testing of ac synchronous superconducting machines which existed; the MIT effort continued into the early 1990s [24].

Also during this timeframe, the US Air Force actively considered the use of high purity, composite, aluminum, cryogenic or "hyperconducting" wire which, although not superconducting, had very low electrical resistance at ~20 K [25]. As already mentioned, the combination of poor cooling and high losses in LTS windings imposed stringent design constraints on the superconductor. These concerns led to the development of a 40 MW generator, incorporating high-purity aluminum in the windings. A 600 kW exciter (shown in Fig. 5) also using the high purity aluminum was constructed for the 40 MW generator and weighed approximately 100 kg [26]. The copper stator windings were designed for operation at 20 K as well.

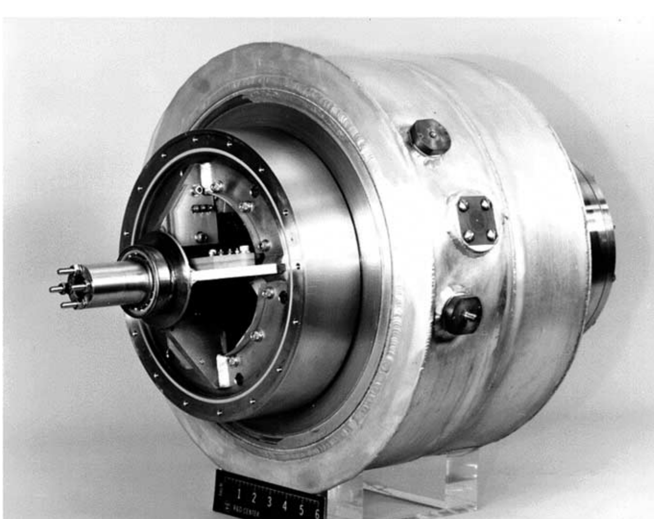

Fig. 5. 600 kW cryogenic aluminum generator (exciter), 1990.

Based on the design and the data collected, it was estimated that the exciter could have provided 1 MW of power, but the machine was not tested to this level. A main drawback of the composite aluminum conductor was the use of liquid hydrogen, which has limited availability in most applications.

Many concluded that HTS conductors should be more fully developed prior to continuing the superconducting generator work [25]. This was not, however, the case in Japan where there were ongoing efforts in NbTi-based generators throughout the 1990s. Successful tests in Japan and the United States of ac superconducting synchronous generators convinced the Japanese government to launch a major national project on the application of superconducting technologies to electric power apparatuses in mid 1987 called the Engineering Research Association Project for Superconductive Generation Equipment and Materials (Super-GM). The first phase of Super-GM consisted of the design, construction, and test verification of three types of 70 MW-class superconducting generators—two slow response and one quick response excitation types [27]. The goal was to establish the technologies sufficiently to design and manufacture a 200 MW-class pilot generator for commercial purposes. The Super-GM program was administered by the New Energy and Industrial Technology Development Organization (NEDO).

For the Super-GM program, testing was completed in 1997 on the first of the 70 MW-class superconducting synchronous generators, slow response excitation type, with testing of the other two occurring in the next couple of years [28]. The slow response excitation type rotors were built by Hitachi and Mitsubishi Electric. Toshiba built the quick response rotor. The LTS NbTi wire for these three rotors was supplied from three different Japanese companies. This program resulted in a record output of 79 MW and the longest continuous operation at 1500 hr [27].

With the development of ultra-fine multifilamentary NbTi conductor, a more ac-tolerant superconducting wire, the prospect of making an all-cryogenic—or fully superconducting—version of the ac synchronous machine was revitalized [29,30]. In France, GEC ALSTHOM built and then tested an all-cryogenic 18 kVA generator in 1990 [31]. As such, the thermal shielding was eliminated between rotor and stator and no electromagnetic shield was employed. All the coils were monolayer and impregnated to minimize wire displacement. Because of the limited range of operating temperatures for LTS conductors, they can be quenched by frictional heating caused by abrupt motion of the wire. Testing of the generator included connection to an industrial power grid. Also in Japan, in 1994, testing of a superconducting armature winding made of NbTi was performed [32]. This was for a 4 pole, 50 Hz, 30 kVA class generator. Countermeasures were taken to minimize the ac loss degradation not only due to the electromagnetic fields the armature windings would experience, but also instabilities caused by conductor motion and vibration.

The armature was wound with a cable consisting of 22 strands specifically designed to minimize ac loss. Testing indicated that the incorporated countermeasures helped to reduce the losses due to ac fields, but the rated armature current was not attained. Both of these efforts attest to the need for proper coil impregnation to prevent superconductor motion.

3.3. BSCCO based generators (mid-1990s-today)

In the US, the Department of Energy (DOE) established the Superconductivity Partnership Initiative (SPI) Program to help fund the industrial development of HTS equipment in 1993. Two of the funded programs initiated in 1994 included a 125 horsepower ac synchronous motor by Reliance Electric and an ac synchronous generator project led by General Electric. The generator program was directed at the conceptual design and assessment of a 100 MVA generator and the construction of a full-scale HTS racetrack coil suitable for use in the generator. The coils, made of the HTS bismuth strontium calcium copper oxide (BSCCO), achieved the high fields necessary and in addition, due to the higher 20 K operating temperature with greater heat capacity, the winding could tolerate a significantly higher transient heating [33]. This implied that less electromagnetic shielding of the field windings would be necessary. The testing provided great confidence in the use of HTS windings.

AMSC and Westinghouse developed more up to date designs for HTS generators in the mid to latter 1990s. One was a conceptual design for a 50 MW, 3600-RPM HTS generator by AMSC [8]. The other effort by Westinghouse was sponsored by the Ballistic Missile Defense Office (BMDO) to provide high power for a mobile radar [34,35]. Westinghouse designed the power system so that the prime power unit would be a diesel engine for an 1800 rpm generator capable of 850 kW at 50 V and 150 kW at 120 V. The rotor included four HTS coils for the field winding and the stator had two sets of windings to supply simultaneously both aforementioned voltages. A Gifford–McMahon refrigerator would provide the necessary cooling for the rotor by heat exchange. The overall effort included the incorporation of the newly developed BSCCO wire into the previously constructed 600 kW exciter for the 40 MW aluminum design by retrofitting the composite aluminum field windings of the exciter with HTS BSCCO field windings. The US Air Force initial funded American Superconductor in 1992 for the fabrication of four demonstration BSCCO coils. In 1996, BMDO funded fabrication of eight identical coils that were tested and met the required specification (72,000 Amp-turn) for incorporation into the exciter. However, after the windings were delivered to Westinghouse to retrofit the exciter, two of the coils were destroyed during a welding process by a sub-contractor on the program. Additional funds were not available to correct this error and final testing of the generator never occurred.

In 2002, the University of Southampton in Great Britain has designed and started to build a simple 100 kVA high temperature superconducting (HTS) demonstrator generator [36]. This particular synchronous generator of the classical superconducting type is a 2-pole machine. The HTS rotor is designed to operate in the range of 57–77 K using either liquid nitrogen or air. To operate at these temperatures using BSCCO conductor, the normal component of the magnetic field will be directed away from the HTS conductor using magnetic invar rings between the adjacent HTS coils. To exclude ac magnetic fields from the rotor, a cold copper screen will be placed around the rotor core.

In 2003, a 1.5 MVA high temperature superconducting generator has been very recently designed, built and successfully tested by the General Electric Company as an engineering prototype for a 100 MVA unit. The HTS coil in the 1.5 MVA demonstrator was designed to operate in the range of 20–40 K and is cooled with a closed cycle helium refrigeration system employing Gifford–McMahon cryocoolers. Predicted thermal losses were compared to those measured during rotor testing at 3600 rpm and found to be in close agreement. GE was just awarded a DOE-SPI contract for the design and development of the 100 MVA HTS generator [37].

3.4. YBCO capable generators (starting 2004)

The US Air Force is also initiating new HTS generator development programs. As of 2004, Long Electromagnetics (LEI) is currently constructing an HTS coil test rig or pseudo generator. The test rig is designed for easier access to the field winding allowing the rotor coils to be replaced with alternate HTS coils for testing at high, >10,000 rpm, rotational speeds. Initial coils of BSCCO will be used, but subsequently made YBCO coils can potentially be placed into the system. Simple stator windings are being included, hence a "pseudo generator". It is expected to provide between 2–3 MW power, but is an open cycle liquid hydrogen initial design (due to the BSCCO coils) as a result of budget constraints. An initial sketch of a more complete generator design is given in Fig. 6. The US Air Force recently initiated a major HTS generator program, awarded to General Electric, in the latter part of 2004 for construction of a fully operational power system using BSCCO wire initially. Both of these systems will have the eventual potential to start the initial incorporation of the YBCO coated conductor into the windings for military generators.

Recently, Rockwell Automation of Ohio just demonstrated for the first time in 2004 a simple generator using only YBCO coils [38]. The generator was built into a standard 5 hp motor frame (Fig. 7). It was a salient pole (iron core), four pole motor with four YBCO field coils provided by SuperPower, Inc. consisting of 20-turns of YBCO superconducting tape, approximately 5.9 m in length and 1.2 cm in width, per coil. The generator had a liquid nitrogen cooled rotor via a shaft center transfer tube and slip rings for the field current supply and for monitoring the coil volt-

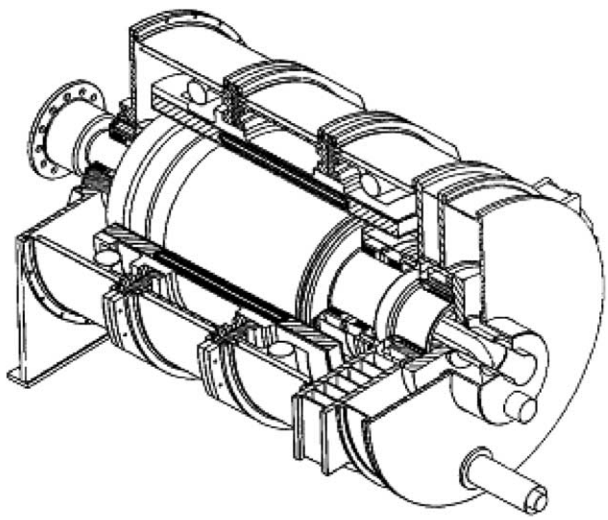

Fig. 6. One Megawatt alternator at 20 K with BSCCO windings, courtesy of Long Electromagnetics.

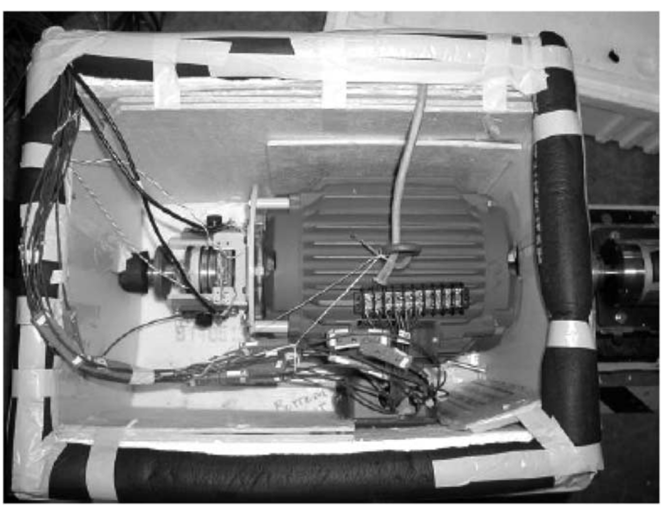

Fig. 7. Rockwell Automation's small developmental motor/generator, 2004.

age and temperature. Load testing of the generator was accomplished at 1800 rpm. Testing consisted of a three phase resistive load, simply light bulbs, to a load of 900 W at a field current of 40 A. The YBCO coil operating temperature was at 81 K.

4. Recent advances in HTS generator-enabling technology

4.1. Refrigeration

The liquid helium temperatures required by LTS wire were a major drawback due to the early technology level of refrigeration equipment. The technological challenge of thermally isolating the cryogenic windings was another problem of earlier development efforts. The significantly higher operating temperatures of the HTS conductors over LTS conductors are a major breakthrough for using superconductors in power generation systems. The operating temperatures for BSCCO (20–35 K) and YBCO (60–77 K) HTS conductors, based on the performance of these conductors in an applied magnetic field, eliminate the need for a continuous supply of liquid cryogens. Even the new superconducting intermetallic MgB_2 has an operating temperature of 20–30 K. Cryogenic refrigerators (cryocoolers) are able to cool the HTS conductors without the complications and logistics of a liquid cryogen tank. Reliable cryocoolers have been commercially available for years, but the larger cooling capacity versions are not necessarily adapted to military environments.

The most used cryocooler is the Gifford–McMahon (G–M) regenerative cycle cryocooler. Unfortunately, the G–M cryocoolers cannot tolerate a battlefield environment and are not highly efficient. The compressors used in G–M cryocoolers cannot be subjected to shock and tilting situations. To counter this deficiency, CFIC Inc., on contract with the US Air Force, has in 2004 recently developed a replacement compressor that is oil free, robust, and operates at any angle. The replacement compressor uses a linear motor to directly drive the pistons that have clearance seals to eliminate the need for oil.

Gifford–McMahon cryocoolers are slowly being replaced by more advanced and efficient cryocoolers such as Stirling and Pulse Tube cryocoolers. Stirling cryocoolers have been used by the military for decades for sensor cooling but these cryocoolers are too small for cooling the larger volume associated with superconducting power applications. Large Stirling and Pulse Tube cryocoolers have more recently become commercially available after more than a decade of development. One cryocooler recently developed by an US Air Force contract for a laser application is a lightweight Stirling cryocooler weighing only 19 lbs and delivering 16 W of refrigeration at 80 K [39]. Atlas Scientific Incorporated is also developing large pulse tube cryocoolers for the Air Force that will potentially provide sufficient cooling for an all-cryogenic generator when an appropriate ac-tolerant HTS conductor is available. This cryocooler is scheduled to be demonstrated in 2005 and will provide 300 W of cooling at 65 K. Both of these cryocoolers use linear motor compressors that enable them to be lightweight, robust, reliable, attitude free and efficient military cryocoolers.

4.2. HTS conductors

HTS conductors typically take the form of a thin tape, allowing them to be bent around relatively small diameters into high density coil windings. The first HTS conductor viable for applications was the bismuth-based superconductor BiSrCaCuO (bismuth strontium calcium copper oxide, BSCCO). Two chemical compositions are available, $Bi_2Sr_2Ca_2Cu_3O_x$ is the most commonly available version. BSCCO wire is a multifilamentary composite superconductor that includes individual superconducting filaments (running the length of the conductor) encased in a Ag or

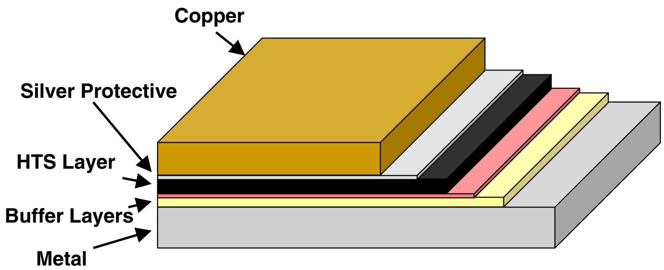

Fig. 8. Typical YBCO coated conductor architecture.

Ag-alloy matrix material. This conductor is made by a powder metallurgy process, and is readily available as a commercial product. Nevertheless, while it has a higher critical temperature, T_c, this "first generation conductor" does not perform as well in the magnetic field and temperature ranges of interest for generators as the more recently developed $YBa_2Cu_3O_7$.

Unlike the powder metallurgy process used to make BSCCO, YBCO conductors are formed as a multilayer coating on a flat substrate, and the associated techniques are referred to as "coated conductor technology". Here an initially flat metal foil, typically a Ni-alloy, is used as a "substrate" upon which buffer and superconducting layers are deposited for epitaxial growth. The initial texture for the epitaxial growth is either formed within the metallic substrate itself by the rolling-assisted, biaxially-textured-substrate (RABiTS) method, or alternatively, in one of the initial buffer layers by using an ion beam assisted deposition (IBAD) or inclined substrate deposition (ISD) technique [40–42]. Fig. 8 provides a sketch of a prototypical YBCO coated conductor architecture. The thin buffer layers prevent metallic diffusion from the substrate into the epitaxial templates and the YBCO layers. After this a protective layer of silver is applied on top of the superconductor to serve as a protective layer (against the environment). An outer copper layer is now typically added on top of this Ag layer to enable current transfer, stabilization, and strand protection.

YBCO has several significant advantages over the currently used first generation wire, as shown in Table 1. One of the primary advantages of YBCO is the possibility of liquid nitrogen temperature (77 K) operation, which would result in substantially relaxed cooling requirements (which translates into weight and cost savings) as compared to 4.2 K operation for LTS and 30 K for first generation HTS conductors. Another advantage of YBCO is its ability to maintain J_cs > 10^5 A/cm^2 in fields up to several tesla; whereas current densities in first generation HTS wires begin to drop off dramatically at fields well under 1 T. Substantial reduction in ac losses as compared to the first generation HTS conductors is also possible with YBCO. Recently, the strain tolerance of the YBCO conductor was demonstrated to be superior to the BSCCO conductor, a critical factor for generator windings [43]. Finally, estimates from two leading US manufacturers [44,45] indicate that conductor cost in terms of $kA/m are expected to be at levels significantly below that of first generation conductors (the exact comparison depends significantly on the machine design operating point).

Advances in the YBCO coated conductors have resulted in dramatic improvements in the quality and length of wire available—from 10^5 A/cm^2 at several centimeter lengths just a few years ago to lengths up to 200 m with over 10^6 A/cm^2 performance [46–51]. These successes have been achieved by improved deposition methods for the HTS layer, more robust and appropriate buffer layer architectures, and fundamental control of the biaxial alignment of the initial buffer layer or underlying metallic substrate.

With the advances mentioned above and the establishment of continuous processing, new research should address the enhancement of YBCO coated conductor performance, allowing additional reductions in size and weight of already compact power systems. Improvements of HTS conductor must focus on maintaining high current densities in fields of a few tesla while simultaneously minimizing ac losses and promoting stability [52–59]. The following sections discuss these necessary conductor enhancements requiring greater flux pinning, lower ac losses, and improved stability and quench protection techniques.

5. Issues and prospects for coated conductor use in generators

5.1. AC loss minimization

Minimizing the ac losses in coated conductors is critical to the development of high power, airborne generators, especially due to the high frequencies of operation (100's

Table 1
Comparison of BSCCO and YBCO for generator applications

Property	BSCCO	YBCO	Operational advantage
Cost	→$50/kA m	→< $10/kA m	Significant savings in purchases; economic viability
Operating temperature (motor, generator, etc.)	20–30 K	60–77 K	Order magnitude reduction in cooling requirements/ refrigeration weight and size
AC loss minimization	Low	Moderate	AC YBCO wire can enable all cryogenic motors & generators (greater weight and size reduction); BSCCO cannot
Engineering current density, self field	10–18 kA/cm^2	→40+ kA/cm^2	Less wire needed for equivalent amp-turns
Pinning properties	<1 A/cm^2, 3 T, 77 K	>10^5 A/cm^2, 3 T, 77 K	BSCCO optimized, YBCO optimization in progress
Critical strain	0.15–0.20% (adequate)	0.30–0.50% (good)	BSCCO tensile strain is just sufficient

Hz or higher) [55,60]. While in dc conditions superconductors do not generate losses, rotating machines and other power devices expose the superconductor to ac fields which do induce energy losses. Conductors must be designed to minimize these losses in order that the size and weight gains realized with the use of superconducting windings are not diminished by the need for a large cooling system. Without an ac-tolerant HTS wire, the construction of a cryogenic stator in the all-cryogenic version of the HTS generator would not be possible. Even for rotor windings, non-synchronous ac effects can generate loss. While ac losses for superconducting machines are lower by design than for Cu-based systems, the efficiency of cooling at cryogenic temperatures is also lower, thus more ac-tolerant conductors are required. In addition, lowered ac losses will increase the machines tolerance of any transient events.

In an ac synchronous generator, variation with time of the rotor-generated magnetic field induces voltages in the stator coils. These voltages cause currents to flow in the armature and out to the load. The alternating current in the armature creates a magnetic field that synchronously rotates with the magnetic flux field caused by the rotating field windings. Therefore, the field of the turning rotor is phase-locked with the stator's field. Under balanced load conditions, the rotor experiences a dc field stemming from the armature. Even so, electrical disturbances in the load can be mirrored in the armature and produce non-synchronous ac effects that influence the field windings of the rotor [89]. These non-synchronous disturbances are mostly a result of unbalanced loads and transient events caused by system faults [7]. The induced time-varying fields in the armature at frequencies other than the synchronous frequency cause compensating ac currents to flow in the field windings, which in turn causing ac losses in the dc superconducting winding. Minimization of these losses requires either the incorporation of warm and/or cold electromagnetic shielding between the armature and field windings, or more ac-tolerant conductors in the rotor which reduces the shielding requirement.

In both the rotor, which is driven by dc current, and the stator, which experiences large, externally induced ac fields, losses in the YBCO coated conductor mainly result from externally applied alternating magnetic fields. The losses have the following components: hysteretic, ferromagnetic, eddy current, and coupling current losses. Losses may also be incurred from self-field transport currents, but this is a smaller effect. Ferromagnetic loss components can be removed by avoiding the use of these materials, typically by using alloys [61]. Hysteretic losses can be reduced by making the strand multifilamentary and reducing the filament width to the smallest level possible [54]. Eddy currents and coupling currents can be reduced by increasing the matrix resistivity; this is particularly so for the substrate although ρ cannot become too high for the final stabilizing layer, or stability will be degraded (see below) [62]. The use of small twist pitch values will also reduce coupling losses [55]. Because of these considerations, previous work on superconducting wire intended for ac applications (in the LTS era) led to NbTi based strands with ultrafine filaments and CuNi matrices [29,30,58]. Creating a multifilamentary coated conductors is more difficult due to the fabrication routes in use, and twisting is even more difficult due to the tape geometry. However, the tape can be subdivided and twisted, resulting in individual filaments of YBCO decoupled through the twist [63,64]. The resulting designs parallel that of traditional LTS wire or conductors, as might be expected, since the requirements are coming from Maxwell's equations which are materials independent.

The Air Force Research Laboratory (AFRL) was perhaps the first to fully demonstrate the reduction of hysteretic losses by subdividing the YBCO into thin filaments [54]. Magnetization vs applied field strength (M–H loops) were measured on short samples of PLD YBCO films which were divided into narrow filaments. The patterning of the YBCO films was accomplished by laser ablation of linear stripes which fully segregated the remaining YBCO filaments. The resulting filamentary structure served to reduce the effective width of the YBCO films and hence the hysteretic loss. The magnetization measurements were taken over the temperature range of 4.2–77 K in applied fields of 0–1.7 T using a vibrating sample magnetometer. The measured hysteretic losses were linearly proportional to filament width, as expected.

However, this demonstration of the effectiveness of striation was limited to small test samples of YBCO films deposited on $LaAlO_3$ single crystal substrate. In addition, only hysteretic loss was measured due to a combination of the low ramping rate of the applied magnetic field in these experiments and the single crystal substrate. Subsequent collaborative efforts led by AFRL showed this loss suppression for striped YBCO coated conductors at higher frequencies [65,66]. AFRL also demonstrated that instead of considering particular frequencies at particular magnetic fields, the sweep rate of the applied magnetic field can be used, and a scaling was devised that allows the contributions of the hysteresis and coupling losses to be quantified and the results of the later experiment to be extrapolated beyond the envelope of accessible field amplitude and frequency [67].

Recently, initial efforts have been established to determine the impact of ac losses in the YBCO coated conductors for generator applications [68]. Even so, additional measurements are necessary on losses associated with true twisting or transposition of the conductor and the effects of demagnetization must also be determined (the conductor in the final coils will have neighboring tapes). To date, measurements have been restricted to small conductor lengths and low $(\mathrm{d}B/\mathrm{d}t)B$ values. Measurements must be made on longer conductors and must be made at higher field sweep rates, or higher magnetic fields and frequencies.

To consider the applicability of ac-tolerant HTS wire in superconducting generators, it is necessary to determine general YBCO conductor ac requirements. With sufficiently ac-tolerant YBCO conductor, unshielded rotor windings are possible. It is especially important to consider the HTS conductor environment in the stator windings, by far the more stringent requirement for high speed generators. Superconducting generators are inevitably closed cycle systems with respect to cryogenic cooling and feasibility of the all cryogenic version must consider a comparison of the total size and weight of the overall cryogenic system (machine plus cooling system) versus an equivalent conventional system (machine plus its cooling system). For megawatt class systems, losses on the order of a few kilowatts have only a minor effect on machine efficiency, so size and weight differences are the primary consideration.

Let us now consider the specifics of loss reduction to reach a conductor specification. With a magnetic field of 1 T and peripheral velocities of 200 m/s, for example, a rms power produced per meter of stator conductor per amp carried in the conductor is 0.1 kW/A m. This implies that for a 5 MW system, 50 kA m of conductor will be needed. It must be remembered that some of the conductor will be outside of the active zone, where the losses are lower This can be reasonably estimated as about double the length of conductor, or 100 kA m. The rotor windings can be estimated to require 400 kA m of conductor in order to obtain proper fields for an air core design (ironless). Next, let us assume that the ac loss budgets will be handled by off-the-shelf refrigeration units, using data for 65 K, with 20 W for the rotor windings with a Stirling cycle cryocooler (∼12 kg) and 220 W for the stator windings with a G–M refrigeration unit (∼180 kg). Of course, if both applications are used, only one refrigerator is necessary. Also, heat leaks will require additional cooling power, but this should be on the same order of magnitude as for the rotor and significantly less than the stator losses. This gives a loss target of 2200 mW/kA m for the stator and ∼50 mW/kA m for the rotor. This number is design specific, but allows a feasibility check of the concept. Again, the stator limitation is driven by reasonable cooling capability (size and weight) and we have assumed no electromagnetic shielding of the field windings. Potential frequency and field conditions of approximately 500 Hz and 1 T in the stator and 2 mT in the rotor are used. Values are shown in Table 2, where the type of conductor needed under these conditions are given for the stator and unshielded rotor.

In the substrate, ferromagnetic and eddy current losses will be the principal forms of ac loss. Additional work has been aimed at the reduction of ferromagnetic losses, especially in the textured substrate approach where Ni–5%W is now the substrate of choice [61]. For IBAD substrates, either inconel or hastelloy is typically used which is already non-magnetic [40,48]. Completely non-magnetic substrates would be preferred, both for the stator and rotor. Substrate-based eddy currents, however, are dominant at higher frequencies [65], both with the hastelloy substrates (non-magnetic) and the NiW substrates. More attention should be paid to reducing the effective resistivity of the substrate, especially in higher frequency applications, as evident in Table 2. Hastelloy has a resistivity of ∼150 μΩ cm which is fairly temperature independent; doubling this resistivity is desirable, further increases would be even better but may prove difficult to achieve with metallic substrates. The use of flexible non-metallic substrates may be possible and should be pursued. In the absence of higher resistivity in the substrate, it will be necessary to reduce the conductor width to much smaller levels.

The width of conductors intended for generator applications has dropped from 1 cm to 4 mm, further reducing this to 2 mm or even 1 mm has been suggested [65]. For the unshielded rotor coil, the losses are manageable for a conductor width of 4 mm. For the stator, it is very difficult to meet the loss requirements in high frequency systems. For a 140 A conductor, these are ∼308 mW/m. Note that moving to a 1 mm wide conductor will effectively lower the eddy

Table 2
AC loss contributions and conductor design for rotor and stator applications

	Rotor		Stator	
Substrate	Non-magnetic, resistivity of ∼150 μΩ cm or greater			
Stabilizer	Cu or Ag with RRR 50 or greater			
Conductor width	∼4 mm		∼2 mm or less	
Filament width	50 μm[a]		5 μm[a]	
Interfilament ρ, μΩ cm	Substrate value		10 × substrate value	
L_p, cm	10[b]		10	
Q_{tot} target, mW/kA m	50		2200	
I_c, A/cm-w, 1 T	140	700	140	700
Q_{tot} target, mW/m	2.8 mW/m (4 mm width)	14 mW/m (4 mm width)	62 mW/m (2 mm width)	308 mW/m (2 mm width)
$Q_{e,substrate}$, mW/m	0.013	0.013	53	53
$Q_{h,SC}$, mW/m	2.8	14	70	350
$Q_{e,stabilizer}$, mW/m	–	–	–	–
Q_{coup}, mW/m	0	0	8	8
Q_{trans}, mW/m	0	0	7[c]	35[c]
Q_{tot}, mW/m	2.8	14	138	446

The rotor windings losses are for non-shielded considerations (500 Hz, 2 mT). Stator conditions are full face on for the whole tape.

[a] Assumes I_c listed below in chart is value after filamentation.

[b] This choice is not critical here since it mainly affects coupling losses: it can be longer.

[c] Assumes an I/I_c factor of ∼70%, refer to text for clarification of this choice.

current losses, but the dominant losses for the listed conditions are the hysteretic losses. Improvement does occur with total losses relative to target values at higher amperage since eddy currents are a sizeable component in the stator windings. Any improvements to the resistivity of the HTS substrate decreases the need for higher critical currents; Los Alamos National Laboratory has demonstrated 1400 A/cm width capability [69]. The copper "stabilizing" layer applied to the top of the superconductor will also result in eddy current losses, unless striped along with the filaments, as described in [65], in which case stabilizer contributions are negligible, both for the stator and the rotor.

Now let us consider the hysteretic component. Table 2 uses 100 μm filaments for the rotor, and 10 μm for the stator. These losses are large for the stator, the hysteretic loss itself being larger than the target value. The hysteretic loss could be reduced by an order of magnitude, putting it on par with the other loss components, but this will require 1 μm filament width which will likely be a severe manufacturing requirement for long lengths of ac-tolerant conductor. The losses can always be removed by a larger refrigeration system, but then system size and weight will suffer even more. In this case, the overall power system efficiency will be the biggest potential advantage of using the superconducting stator windings in high frequency applications, if desired, since kilowatts of power input to the refrigeration component is substantially lower than multimegawatts of power output. The coupling losses are quite low for the rotor, and the twist length requirement is not especially strong. An alternate possibility to lower losses is to more aggressively pursue the development of YBCO coated conductor that is not in flat tape form (two dimensional), but in a three dimensional geometry. HTS conductor in this form may allow a greater ease in creating transposed wire geometries for ac loss reduction.

As just mentioned, if possible, filaments should be twisted and/or transposed some way other than the simple twisting of the tape as suggested in [63]. Simple twisting reduces J_e greatly, if special placement of the twist location is not considered, and cannot be used in these applications. On the other hand, other kinds of transposition are possible [64,68,70]. For example, the very act of winding a rotor race track coil can potentially induce an effective twist pitch equal to roughly twice the coil length, because of the field and coil geometry. Thus in Table 2 we have used $L_{eff} = 40$ cm, since we assume, for sake of argument, that the rotor coil length is 20 cm (and we then use $L_{eff} = 2L$) to calculate coupling current losses in the rotor. For the stator coil, winding for transposition or otherwise introducing transpositions will be more difficult, although some possibilities are being explored [68,70]. We note that a stringent neutral axis geometry may be important for stator applications, as it will potentially allow much greater bending [71]. If a method can be devised to transpose the filaments without physically bending the superconducting material itself (as part of the HTS coated conductor), issues associated with these limitations can be largely avoided. Some method have been recently considered of intertwining the filaments of a HTS coated conductor on a single tape, but this is still under investigation [64,68,70].

It is important to keep in mind that stator values are for full face-on fields and not all regions will suffer this requirement. On the other hand, in those regions that are not face-on, there will be some additional transport current loss. Transport current losses are much larger when there is no magnetic field to decouple the filamentary currents. We have in general not discussed any "de-rating" of the current from I_c for operational safety. As the operational current becomes a smaller fraction of I_c, transport losses also diminish. In the end regions of the stator windings, the magnetic field will decrease and the I/I_c will increase causing competing factors in transport current losses. Either way, changes in the losses projected will be affected since here they are fundamentally based on W/kA m.

One additional consideration is the relative advantage with respect to losses of operating at a given temperature. As temperature is lowered the current capacity of the wire goes up. Although the loss per meter is greater at the higher amperage, less wire is needed for a given power rating. Table 3 provides some relative data on recent conductor properties at different temperatures (Table 3 is discussed more below). Ultimately, YBCO conductor critical currents may be higher than these present values. By using this data in combination with that from Table 2, Table 4 is created which makes this comparison versus operating temperature. The Watt per weight correction factor uses

Table 3
J_c and J_e *present* performance and target for YBCO and BSCCO

Temperature T (K)	YBCO at 1 T				Bi2223 at 1 T			J_{target} (A/mm^2)
	$I_{c\perp}$ @ 1 T (A/cm-width)	J_e, $B_\parallel$ (A/mm^2)	J_e, B_{perp} (A/mm^2)	J_w[a] (A/mm^2)	J_e, $B_\parallel$ (A/cm)^2	J_e, B_{perp} (A/cm^2)	J_w[a] (A/cm^2)	
27	700	–[b]	825	660	480	220	175	150–400
65	140	–[b]	165	130	160	–	–	150–400
77	40	165[c]	50	40	45	–	–	150–400

[a] Here we assume that the insulation requires ~20% of the winding.
[b] Data not available.
[c] Extrapolated data.

Table 4
AC loss comparison versus refrigeration requirement at different temperatures

	Stator, 2 mm width conductor		
Temperature	77 K	65 K	27 K
Conductor, $B_{perp} = 1$ T (Amp/cm-width)	40	140	700
Loss, Q_{tot} from Table 2 (mW/m)	83	138	446
Total loss, given power (Watts)	1037	493	318
Cryocooler weight correction factor	0.88	1	2.75
Cryocooler size (arbitrary units)	913	493	875

data based on a Gifford–McMahon cryorefrigerator from Cryomech, the AL330, which operates in the temperature ranges given. A comparison for the rotor windings is not given in Table 4 since the losses are essentially hysteretic and, as such, the total loss will be the same at each temperature, making the highest operating temperature the most efficient with respect to refrigeration requirements. Note that the data in the table suggests that for the given conditions, 65 K may be the preferred operating temperature with respect to overall weight addition. Indeed, cryocoolers optimized at the different temperatures can be considered.

Alternate values can be used in lieu of those presently chosen in Table 2, but demonstrate the thought process, as with Table 4. Even so, the use of these values clearly indicate that the use of superconducting stator windings for high speed generators, subject to high sweep fields, will be difficult to achieve a lower size and/or weight compared to the classic superconducting rotor only system. Some assumptions made could be refined and may (or may not) lead to slightly more tolerable results, but the assumptions presently used allow a good initial assessment. On the other hand, low speed generators (and motors) may very well allow all cryogenic models. One subject not considered here is the issue of potential windage losses in the all cryogenic model. Windage losses result from the friction generated in the gap between the stator and the high speed rotor. Large heat losses produced by the high velocity motor will occur if the gap is filled with a cooling gas depending on design.

5.2. Increased J_c and J_e

One of the critical issues for enabling superconducting generators is increasing J_c and J_e to the level that higher operating temperatures are practical. HTS conductors are in principle usable at temperatures up to their T_c. However, from a practical perspective, minimum current levels are required to make useful machines. A J_e of 150 A/mm^2 is a minimal target for the field windings, 200–250 A/mm^2 is a reasonable moderate target, and a highly aggressive target is 400 A/mm^2. This parameter is defined as the operating current divided by the total cross section of the winding, and includes not only the non-superconucting portions of the tape but the insulation between conductor layers. This target is of course somewhat moveable, trading off with machine size and cooling efficiency. For some specific comparisons of these targets to present day industrial accomplishments: BSCCO as a commercial item and YBCO as industrial developmental progress [72,73], see Table 3. Values are given for a 1 T magnetic field (as a representative example) oriented both parallel (best case) and perpendicular (worst case) to the face of the tape. Again, the desired current levels in the windings will not be at 100% of I_c.

With an overall conductor thickness of ~150 μm (again including substrate, stabilizing layer, HTS layer, etc.), then a $J_c > 1.5 \times 10^6$ A/cm^2 is necessary for a 2 μm thick YBCO layer for the moderate target. Although at first glance it may appear that this is already accomplished, deeper consideration shows that significant improvements are necessary. The 10^6 A/cm^2 level performance mentioned should be for the in-field, operating temperature of the conductor. Current substrate thicknesses must be reduced by 50% or more. In addition, thicker YBCO layers and/or higher J_c may be necessary to compensate as well as lower operating temperatures than 77 K. Limitations to consider are a lower end temperature of 60–65 K (lower temperatures will require substantially larger cooling systems) and J_c being at the higher end of 6–8 × 10^6 A/cm^2 (reaching the J_c of single crystals). One last point is the angular dependence of the YBCO coated conductor. Due to the anisotropic behavior of HTS conductors, J_c can potentially drop by an order of magnitude when going from the *a*,*b*-axis magnetic field orientation to the *c*-axis orientation. Angular dependence must be accounted for in the generator windings since the conductor is only as effective as the weakest section resulting from the worse case, which is a function of both field strength and angular orientation. Although fields may not be oriented exactly in the *c*-axis direction, this is not always the weakest direction for the conductor.

Naturally, the J_e of a given conductor (defined with respect to the total area of the conductor) increases as we decrease the temperature. On the other hand, what we would prefer is to increase J_e at a given operating temperature. There are three temperature "regimes" at which we can aim: 20–60 K (cryocooler), 65–70 K (cooled LN_2) and liquid nitrogen. We would prefer to push the usable operating range of the coated conductors into the highest possible temperature ranges. This can be done in two basic ways; increasing the intrinsic J_c of the superconductor, or decreasing the non-superconducting area of the conductor. Any increases in these areas would be additive. Presently, significant work is ongoing in both directions.

In the area of pinning enhancement, one method recently discovered by Haugan et al. is that of a nanoparticulate dispersion of Y_2BaCuO_5 (Y211)—a non-superconducting phase of YBCO—incorporated into the superconducting phase of YBCO (Y123) [74,75]. In this particular case, the nanoparticles were introduced by a composite multilayer structure which was created by growing the Y123 layer and Y211 nanoparticles by multiple, consecutive pulsed laser depositions using the respective targets. Because of the lattice mismatch between the insulating Y211 and superconducting Y123 phases, ~2–9%, the Y211 growth occurred as an island-growth mechanism in each layer with ~10 nm size disc-shaped nanoparticles with a surface particle density > 10^{11} cm^{-2}. The Y123 phase maintained excellent epitaxy and in-plane orientation even with the Y211 particles, resulting in J_cs of 3–5 times that of standard YBCO at applied fields of a few tesla, 30–77 K.

Also being considered for improvement to the YBCO coated conductor is the effect of chemical composition variations on the flux pinning and physical properties of $(Y,RE)_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ superconductors [76–78]. Recent progress by other groups also indicate potential solutions to improvement in flux pinning [79,80]. Pinning mechanisms other than nanoparticulate dispersions and YBCO lattice doping include defect introduction and propagation and controlled damage introduction such as irradiation [81,82]. A critical next step is to transition these pinning methods to industrial processes. There are also parallel efforts focused on increasing J_e. One of the complications that has made this presumably straightforward approach more difficult has been a general fall-off in J_c as layer thickness increases. Nevertheless, progress is being made in this area [69].

5.3. Management of stability and protection

HTS wire, which operates at substantially higher temperatures than LTS wire, allows the use of simpler, more efficient refrigeration systems. Higher operating temperatures also increase the stability margin of the HTS conductor compared to LTS conductors. One of the fundamental reasons for this is that the conductor's specific heat increases greatly at higher temperatures [7]. A direct result of this is that the flux jump stability criterion for filament size, so important for LTS filament size, is non-critical for HTS at 77 K. This increase in heat capacity also increases the minimum quench energy from around 1–10 mJ for NbTi/Nb_3Sn to 5–75 J for YBCO at 77 K, thus the ability of HTS conductors to tolerate conductor movement due to any disturbance (e.g., conductor motion) is also greatly improved over LTS conductors [83].

Even though the HTS conductors at 77 K have a much greater intrinsic stability margin which makes quenches less likely, they can still occur as recently demonstrated in a HTS developmental motor [84]. The quench in the Rockwell 1600 hp demonstration HTS motor resulted in permanent coil damage in less than 10 s. The quench current was 31 A compared to the critical current of 25 A. A Cryomagnetics developmental HTS magnet had quenched, but this resulted from failure of the copper downleads, not the HTS conductor, when testing the magnet out of the intended operational parameters [85]. Because of the possibility of quench, the conductors must be protected in the case that a quench does occur, or the coil windings are more than likely to be irreparably damaged.

As mentioned, HTS conductors will inherently operate at a greater stability margin than that of LTS conductors. However, the HTS conductors in the rotor windings will in many cases be conduction cooled since they are generally in potted magnetic coils, which make Stekly stability (or fully cryostable operation) difficult to achieve. In a fully cryostable operation, the current is transferred to the stabilizer during a quench and the heat generated in the stabilizer is fully removed by heat transfer to the cryogenic bath. With a lack of sufficiently high heat transfer, the coils may be considered adiabatic in nature, and they will operate on the basis of a stability margin. Fortunately, this margin is quite high, as noted above. Consideration of these issues leads to two forms of quench protection, passive and active.

Passive protection relies on the quick spreading of the normal zone within the conductor. However, the normal zone propagation (NZP) velocity is typically inversely proportional to the minimum quench energy. Presently, the NZP velocity for HTS conductors is more like mm/s, as opposed to the LTS case, where it is m/s. Improvement to the NZP will require the use of materials with high thermal conductivity such as more thermally conductive dialectics used to insulate the conductor or pot the windings. Thermal contact of these materials with the YBCO is obviously necessary; for example, the substrate in the YBCO coated conductor is partially isolated from the YBCO layer by buffers layers which are not optimized with respect to thermal conductivity. The concept of the conductor being surrounded by a stabilizing layer [46,57] can be useful in promoting both the radial and transverse spread of heat. Paramount is to prevent the destruction of the tape and coil, not only due to the dumping of energy during the quench finale, but also due to significant heating that damages the superconducting tape's properties—YBCO can lose oxygen content as temperature become much more than 700 °C permanently lowering its current carrying capacity.

Active quench protection amounts to detecting the presence of a quench, and shutting down the system before it can burn out. We must have two things for an active quench protection scheme. First, we need to have enough normal conductor to carry the current in the place of the superconducting element while the quench is being detected and the system is being shut down. Second, we must in fact detect the quench and shut the system down. The first objective is met by the inclusion of a conductive layer, e.g. Cu or Ag, in direct contact with the YBCO. The amount needed can be found by using Iwasa's treatment [83] where the time constant of magnet decay is assumed to set the time over which the matrix must withstand the current. On the other hand, Iwasa has pointed out [private communication, April 2005] that the time constant of decay may be small to the system delay required to shut the current off. This may be as much as 1 s, or at minimum as little as 0.1 s. Using the simple expression (related to that in [83]) of $J_m < (Z/\tau)^{1/2}$ and setting $Z = 10^{17}$ A^2 s/m^4, we see that $J_m = 3 \times 10^8$ A/m^2 to 3×10^9 A/m^2 for 1 s and

0.1 s delay times, respectively. Here J_m is the current density in the matrix during a quench. If the operating current of the strand during normal operation is 1000 A, this leads to stabilizer thicknesses of 30–300 μm for 0.1 s and 1 s.

The level of stabilizer to be added should be this much to allow for proper protection. Further addition of stabilizer is unwanted because it will decrease J_e. In addition, more Cu also lowers the voltage produced in a quench, and makes detection more difficult (and thus slower). Thus, the choice of stabilizer level is a tradeoff between detection and protection. Some estimates for YBCO conductors have been made by Iwasa [86], giving 30 mV as a rough detection level voltage. In fact, one of the most difficult issues related to the use of coated conductors for generator applications is quench detection. Because of the slowing growing normal zone, the quench voltage develops comparatively slowly. In addition, the ac environment makes its detection above the noise more difficult. For this reason, other methods of detection have been proposed [87,88], although these have their own problems.

5.4. Other considerations

A few other considerations must be made as we develop coated conductors for motor/generator applications. It is expected that the final magnet will be potted, thus insulation and impregnation schemes are very important for proper performance. Estimates of stress on the conductor vary, but stresses may reach 100–200 MPa [88]. In general, the response of the conductor and magnet to thermal cycling, field cycling, and mechanical cycling must be understood and controlled. Thermal management distribution issues should include cryogenic to room temperature thermal issues (downleads, connection leads, and seals) as well as steady state issues.

6. Conclusion: prospects for high power density superconducting generators

Future military systems will depend on high electrical power input that will exceed the megawatt level. The power subsystems required for these applications must often be packaged into limited space and within strict weight limits on either ground-mobile or airborne platforms. Generators made using HTS conductor can enable megawatt-class airborne or ground-mobile power systems that are lightweight and compact. Key to these generators are the HTS conductors recently made available and advances in cryogenic refrigeration systems. The HTS YBCO coated conductor has demonstrated the best performance and is capable of meeting requirements of a superconducting power system. YBCO coated conductors can be further enhanced by better flux pinning methods and development of an ac-tolerant architecture, which recent research has shown to be possible. Improvements in these enhancement areas as well as improved stability will lead to unprecedented power densities in generators.

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References

[1] Active denial. III-Vs Reviews 2004;17(5):10.
[2] Tolliver JC, Rhoads GL, Barnes PN, Adams SF, Oberly CE. Superconducting generators: Enabling airborne directed energy weapons, international energy conversion engineering conference. AIAA Paper 2003-5917.
[3] Gubser DU. Superconducting motors and generators for naval applications. Physica C 2003;392–396:1192.
[4] Fair HD. Electromagnetic launch science and technology in the United States. IEEE Trans Magn 2005;41(1):158.
[5] McNab IR. Pulsed power for electric guns. IEEE Trans Magn 1997;33:453.
[6] Eckel P, Snitchler G. 5 MW High temperature superconducting ship propulsion motor design and test results. In: Electric machinery technology symposium, Anta, PA, 28 January 2004.
[7] Blaugher RD. Power systems, generation, and storage in power applications of superconductivity in Japan and Germany. WTEC Panel Report 1977.
[8] Kalsi SS. Development status of superconducting rotating machines. In: IEEE PES meeting proceedings 2002, IEEE CD Cat. No. 02CH37309C.
[9] American Superconductor Corporation, website, http://www.amsuper.com.
[10] Superczynski MJ, Waltman DJ. Homopolar motor with high temperature superconductor field windings. IEEE Trans Appl Supercond 1997;7(2):513.
[11] Oberhauser CJ, Kinner HR. Some considerations in the design of a superconducting alternator. Adv Cryogenic Eng 1968;13.
[12] Smith Jr JL, Kirtley Jr JL, Thullen P. Superconducting rotating machines. IEEE Trans Magn 1975;11:128.
[13] Edmunds JS. Superconducting generator technology – an overview. IEEE Trans Magn 1979;15:673.
[14] Parker Jr JH, Blaugher RD, Patterson A, Vecchio PD, McCabria JL. A high speed superconducting rotor. IEEE Trans Magn 1975;11:640.
[15] Oberly CE. Air force applications of lightweight superconducting machinery. IEEE Trans Magn 1977;13:260.
[16] Fujino H. Technical overview of Japanese superconducting generator development program. IEEE Trans Magn 1983;19:533.
[17] Maki N, Yamaguchi K, Takahashi M, Shiobara R. Development of superconducting ac generator. IEEE Trans Magn 1988;24:792.
[18] Smith Jr JL. Overview of the development of superconducting synchronous generators. IEEE Trans Magn 1983;19:522.
[19] Sabrie JL, Goyer J. Technical overview of the French program. IEEE Trans Magn 1983;19:529.
[20] Brunet Y, Tixador P, Laumond Y, Sabrie JL. First electrical tests on a machine with an ac superconducting stator winding. IEEE Trans Magn 1988;24:796.
[21] Intichar L, Lambrecht D. Technical overview of the German program to develop superconducting ac generators. IEEE Trans Magn 1983;19:536.
[22] Glebov IA, Shaktarin VN. High efficiency and low consumption material electrical generators. IEEE Trans Magn 1983;19:541.
[23] Smith Jr JL, Kirtley Jr JL, Sunder S, Umans S. Performance of MIT 10 MVA superconducting generator rotor. IEEE Trans Appl Supercond 1995;5:445.
[24] Kirtley Jr JL, Smith Jr JL, Umans SD. Ten MVA superconducting generator development: status at the end of 1989. IEEE Trans Energy Conv 1991;6:274.
[25] Oberly CE, Ho JC. The origin and future of composite aluminum conductors. IEEE Trans Magn 1991;27:458.

[26] Eckels PW. Cryogenic generator cooling. Adv Cryogenic Eng 1990; 35B:1639.
[27] Shimada T, Shibuya M, Takahashi R, Imai Y, Kusafuka H, Shiobara R, et al. Recent progress on 70 MW class superconducting generators. IEEE Trans Appl Supercond 1999;9:1189.
[28] Oishi I, Nishijima K. Summary of development of 70 MW class model superconducting generator—research and development of superconducting for electric power application. Cryogenics 2002;42: 157.
[29] Cave JR, Fevrier A, Verhaege T. Reduction of ac losses in ultra-fine multifilamentary NbTi wires. IEEE Trans Magn 1989;25:1945.
[30] Fevrier A. Latest news about superconducting a.c. machines. IEEE Trans Magn 1988;24:787.
[31] Tixador P, Brunet Y, Vedrine P, Laumond Y, Sabrie JL. Electrical tests on a fully superconducting synchronous machine. IEEE Trans Magn 1991;27:2256.
[32] Takao T, Akita S, Torii S, Ohishi K, Shimizu H. Development and electrical test of a 30 kVA class fully superconducting generator. IEEE Trans Magn 1994;30:2308.
[33] Salasoo L, Herd KG, Laskaris ET, Hart Jr HR, Chari MVK. Test Results for a Bi-2223 HTS racetrack coil for generator applications. IEEE Trans Appl Supercond 1997;7:535.
[34] Rodenbush AJ, Young SJ. Performance of high temperature superconducting coils for implementation into megawatt class generators. IEEE Trans Appl Supercond 1999;9:1233.
[35] Singh SK, Scherbarth DW, Ortoli ES, Repp JR, Christianson OR, Parker Jr JH, et al. Conceptual design of a high temperature superconducting generator. IEEE Trans Appl Supercond 1999;9: 1237.
[36] Al-Mosawi MK, Beduz C, Goddard K, Sykulski JK, Yang Y, Xu B, et al. Design of a 100 kVA high temperature superconducting demonstration synchronous generator. Physica C 2002;372–376:1539.
[37] Fogarty JM. Development of a 100 MVA high temperature superconducting generator. In: IEEE power engineering society meeting 2004, Denver, CL.
[38] Schiferl R. Development of ultra efficient electrical motor systems. In: DOE Annual Superconductivity Peer Review Meeting 2004, Washington, DC; Schiferl R, Rockwell Automation Superconducting Motor Technology, prepared presentation 2004.
[39] Penswick LB, Hoden BP. Development of a light weight linear drive cryocooler for cryogenically cooled solid state laser systems. Cryocoolers 1999;10:77 and Proceedings of the 10th international cryocooler conference, May 26–28, 1998.
[40] Groves JR, Arendt PN, Foltyn SR, Jia Q, Holesinger TG, Kung H, et al. Physica C 2002;382:43.
[41] Goyal A, Lee DF, List FA, Specht ED, Feenstra R, Paranthaman M, et al. Physica C 2001;357–360:903.
[42] Balachandran U, Ma B, Li M, Fisher BL, Koritala RE, Miller DJ, et al. Physica C 2003;392–396(2):806.
[43] Ekin J, Cheggour N, Clickner C, Arecht M, Adare A. Electromechnaical studies for coated-conductor development. DOE Annual Peer Review—Superconductivity Program for Electric Systems, July 23–25, 2003.
[44] American Superconductor Corporation, http://www.amsuper.com.
[45] SuperPower, Inc., http://www.igc.com/superpower.
[46] Yamada Y, Watanabe T, Muroga T, Miyata S, Iwai H, Ibi A, et al. Activity in SRL Nagoya Coated Conductor Center for long YBCO coated conductor by IBAD + PLD method. In: International cryogenic materials conference, August 28–September 2, 2005;
Qiao Y, Chen Y, Xiong X, Li Y, Hou P, Xie YY, et al. Advances in scale-up of second generation HTS conductors at SuperPower. In: International cryogenic materials conference, August 28–September 2, 2005.
[47] Iijima Y, Kakimoto K, Sutoh Y, Ajimura S, Saitoh T. Development of long Y-123 coated conductors for coil-applications by IBAD/PLD method. In: Applied Superconductivity Conference, October 4–8, 2004.
[48] Selvamanickam V, Lee HG, Li Y, Xiong X, Qiao Y, Reeves J, et al. Physica C 2003;392–396:859.
[49] Verebelyi DT, Schoop U, Thieme C, Li X, Zhang W, Kodenkandath T, et al. Supercond Sci Technol 2003;16:L19.
[50] Kakimoto K, Iijima Y, Saitoh T. Physica C 2003;392–396(2):783.
[51] Usoskin A, Freyhardt HC, Issaev A, Dzick J, Knoke J, Oomen MP, et al. IEEE Trans Appl Supercond 2003;13:2452.
[52] Bray JW. Application of superconducting materials to power equipment. J Electron Mater 1995;24:1767.
[53] Haugan T, Barnes PN, Wheeler R, Meisenkothen F, Sumption M. Addition of nanoparticle dispersions to enhance flux pinning of the type II high temperature superconductor $YBa_2Cu_3O_{7-x}$. Nature 2004;430:867.
[54] Cobb CB, Barnes PN, Haugan TJ, Tolliver JC, Lee EJ, Sumption MD, et al. Hysteretic loss reduction in striated YBCO. Physica C 2002;382:52.
[55] Oberly CE, Rhoads GL, Barnes PN, Long L, Scott DJ, Carr Jr WJ. The importance of interfilamentary barrier resistance in YBCO coated conductor to minimize ac losses. Adv Cryogenic Eng 2002;48B:621.
[56] Sumption MD, Collings EW, Barnes PN. AC loss in striped (filamentary) YBCO coated conductors leading to designs for high frequencies and field-sweep amplitudes. Supercond Sci Tech 2005;18: 122.
[57] Iwasa Y, Jankowski J, Hahn S-Y, Lee H, Bascunan J, Reeves J, et al. Stability and quench protection of coated YBCO "Composite" tape. In: Applied superconductivity conference, October 4–8, 2004; to appear in Supercond Sci Tech.
[58] Iwasa Y. Stability and protection of superconducting magnets—a discussion. In: Applied superconductivity conference, October 4–8, 2004; to appear in Supercond Sci Tech.
[59] Larbalestier D, Gurevich A, Feldmann DM, Polyanskii A. High T_c superconducting materials for electric power applications. Nature 2001;414:368.
[60] Barnes PN, Rhoads GL, Tolliver JC, Sumption MD, Schmaeman KW. Compact, lightweight superconducting power generators. IEEE Trans Magn 2005;41:268.
[61] Ijaduola AO, Thompson JR, Goyal A, Thieme CLH, Marken K. Magnetism and ferromagnetic loss in Ni–W textured substrates for coated conductors. Physica C 2004;403:163.
[62] Collings EW, Sumption MD. Stability and AC losses in HTSC/Ag multifilamentary strands. Appl Supercond 1995;3:551.
[63] Carr Jr JW. Paper CPD9 presented at Cryogenic Engineering Conference—International Cryogenic Materials Conference, Portland, OR, 1997.
[64] Barnes PN, Levin GA, Varanasi C, Sumption MD. Low AC loss structures in YBCO coated conductors with filamentary current sharing. IEEE Trans Appl Supercond 2005;15:2827.
[65] Sumption MD, Collings EW, Barnes PN. AC loss in striped (filamentary) YBCO coated conductors leading to designs for high frequencies and field-sweep amplitudes. Supercond Sci Tech 2005;18:122.
[66] Amemiya N, Kasai S, Yoda K, Jiang Z, Levin GA, Barnes PN, et al. AC loss reduction of YBCO coated conductors by multifilamentary structure. Supercond Sci Technol 2004;17:1464.
[67] Levin GA, Barnes PN, Amemiya N, Kasai S, Yoda K, Jiang Z. Magnetization losses in multifilament coated superconductors. Appl Phys Lett 2005;86(1):072509.
[68] Sumption MD, Barnes PN, Collings EW. AC losses of coated conductors in perpendicular fields and concepts for twisting. IEEE Trans Appl Supercond 2005;15:2827.
[69] Foltyn S, Arendt P, Wang H, Jia Q, DePaula R, Stan L, et al. High current coated conductors based on IBAD MgO and PLD YBCO. Presented at the Department of Energy Superconductivity for Electric Systems Annual Peer Review, Washington, DC 2004.
[70] Sumption MD. Various conductor options for YBCO loss suppression. Submitted as part of the final report to the Air Force Research Laboratory for the Propulsion Directorate Summer Faculty Program, 2004.

[71] Verebelyi D, Harley E, Scudiere J, Otto A, Schoop U, Thieme C, et al. Practical neutral-axis conductor geometries for coated conductor composite wire. Supercond Sci Technol 2003;16:1158.
[72] Rupich M. YBCO coated conductor status. Air Force Office of Scientific Research High Temperature Superconducting Coated Conductor Review, Orlando, FL, 2005.
[73] American Superconductor Corporation, HTS High Strength Wire fact sheet, WFS-HS-0904, 2004.
[74] Haugan TJ, Barnes PN, Maartense I, Lee EJ, Sumption M, Cobb CB. Island growth of Y_2BaCuO_5 nanoparticles in $(211_{\sim 1.5nm}/123_{\sim 10nm})$xN composite multilayer structures to enhance flux pinning of $YBa_2Cu_3O_{7-d}$ films. J Mater Res 2003;18:2618.
[75] Haugan T, Barnes PN, Wheeler R, Meisenkothen F, Sumption M. Addition of nanoparticle dispersions to enhance flux pinning of the type II high temperature superconductor $YBa_2Cu_3O_{7-x}$. Nature 2004;430:867.
[76] Haugan TJ, Evans JM, Tolliver JC, Maartense I, Barnes PN, Wong-Ng W, et al. Flux pinning and properties of solid-solution $(Y,Nd)_{1+x}Ba_{2-x}Cu_3O_{7-d}$ superconductors processed in air and partial oxygen atmospheres. Ceram Trans 2004;149:151.
[77] MacManus-Driscoll JL, Foltyn SR, Maiorov B, Jia QX, Wang H, Serquis A, et al. Rare earth ion size effects and enhanced critical current densities in $Y_{2/3}Sm_{1/3}Ba_2Cu_3O_{7-x}$ coated conductors. Appl Phys Lett 2005;86:032505.
[78] MacManus-Driscoll JL, Foltyn SR, Jia QX, Wang H, Serquis A, Maiorov B, et al. Systematic enhancement of in-field critical current density with rare-earth ion size variance in superconducting rare-earth barium cuprate films. Appl Phys Lett 2004;84:5329.
[79] Civale L et al. Understanding and improving pinning in coated conductors. Presented at the Department of Energy Superconductivity for Electric Systems Annual Peer Review Washington, DC, 2004.
[80] Goyal et al. RABiTS substrates research & development. Presented at the Department of Energy Superconductivity for Electric Systems Annual Peer Review Washington, DC, 2004.
[81] Matsumoto K, Horide T, Osamura K, Mukaida M, Yoshida Y, Ichinose A, et al. Enhancement of critical current density of YBCO films by introduction of artificial pinning centers due to the distributed nano-scaled Y2O3 islands on substrates. Physica C 2004;412–414:1267.
[82] Kell JW, Haugan TJ, Locke MF, Barnes PN. Tb and Ce doped Y123 films processed by pulsed laser deposition. IEEE Trans Appl Supercond 2004;15:3726.
[83] Iwasa Y. Case studies in super conducting magnets. New York: Plenum Press; 1994. 2nd edition expected soon.
[84] Shoykhet B. Development of ultra efficient HTS electric motor systems. Presented at DOE Wire Development Workshop, St. Petersburg, FL, January 2005.
[85] Cryomagnetics internal report, 2004.
[86] Iwasa Y, Voltage based detection of quench. Presented at the Quench and Stability Workshop, Orlando, FL, January 2005.
[87] Seimens Presentation at SCEnet, Twente, The Netherlands, March 2005.
[88] Quench and Stability Workshop, Orlando, FL, January 2005.
[89] Sivasubramaniam K, Huang X, Ryan D, Weeber K, Bray J, Laskaris E, et al. AC losses in a high temperature superconducting generator. IEEE Trans Appl Supercond 2005;15:2162.