

Incorporating YBCO Coated Conductors in High-speed Superconducting Generators

Paul N. Barnes, George A. Levin, and Edward B. Durkin

Abstract-- With the development of airborne directed energy applications, power generation systems above the megawatt level will be required. Superconducting generators can address this need. Recently, several successful rotating machinery projects demonstrated the practicality and feasibility of the technology using the high temperature superconducting BSCCO wire. With progress in manufacturing long continuous lengths of the superconducting YBCO coated conductors, addition improvement can be made to these superconducting devices. This paper will briefly address the prospects for employment of the YBCO coated conductors in future power machinery demonstrations.

Index Terms—high-temperature superconductors, YBCO, superconducting tapes, superconducting wire, superconducting rotating machines, superconducting materials, YBCO coated conductors.

I. INTRODUCTION

A prominent need of future airborne power systems of megawatt-class output is minimizing the size and weight of the power generation and ancillary support systems. One approach for achieving higher power density within the generator is to use high speed generators with substantially increased magnetic flux density. This can be achieved by using superconducting wire that combines high engineering current density and low losses [1] – [3].

The central challenge is to effectively integrate the superconducting coil and its cryo-cooling subsystem. This problem is magnified at the higher rotating speeds, if the conductor and cooling system are rotor-mounted. The added challenge of a power generation system with high power density is that the increased heat generation per-unit mass requires a closely-integrated and efficient integrated thermal management system.

Most power machinery demonstrations to date have used the bismuth strontium calcium copper oxide (BSCCO) superconductor being the first HTS conductor to be scaled up [1]. However, a newer yttrium barium copper oxide (YBCO) superconductor has been developed that has in the past year

been scaled to lengths useable in power application demonstrations. YBCO has several significant advantages over the BSCCO wire: in-field operation at liquid nitrogen temperatures while maintaining high critical currents (J_c) in magnetic fields up to several Tesla, the ability to reduce ac losses in the architecture, improved strain tolerance, and lower production costs. Scale-up of the YBCO coated conductors by manufacturers has improved the quality and length of wire available—from 10^5 A/cm², self-field, at several centimeters length a few years ago to lengths of 600 m and longer with 10^6 A/cm² performance [4], [5].

II. MULTIMEGAWATT ELECTRIC POWER SYSTEM

A recent effort by the U.S. Air Force has been to advance the power technologies in support of high power applications (HPA) being placed on airborne platforms. In order to meet the large onboard electrical power demands, it is necessary to develop the required power generation, distribution, and conditioning technologies required for the airborne use of these applications. One program is the megawatt-level electric power system (MEPS). The Broad Agency Announcement for the program stated the specific objective of the MEPS program was the development and testing of the superconducting power system for airborne HPA.

In 2004, the Air Force Research Laboratory (AFRL) contracted with General Electric (GE) to design, build, and test a MEPS configuration including a superconducting generator, cooling systems, and power conditioning system. The cornerstone of the program was a high-temperature superconducting (HTS) generator which would demonstrate technologies leading to later HTS machine designs with specific power ratios exceeding 4.0 kW/lb (8.82 kW/kg). The machine configuration chosen by GE for design was a homopolar inductor alternator (HIA) which locates the superconductor coil within the stator, thereby eliminating rotational loads on the coil while also simplifying the rotor design to a more rugged structure. Removing the HTS coil from the rotor also allows higher rotating speeds which improves the overall power density.

GE has completed a 1-megawatt class HTS generator in early 2007, and the following tests provided the first successful full-power run of an HTS machine for the USAF. The generator produced 1.3 MW output at its design speed of 10^4 rpm, and achieved 97% overall efficiency even accounting for cryo-cooler losses. This generator demonstration not only

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14. ABSTRACT With the development of airborne directed energy applications, power generation systems above the megawatt level will be required. Superconducting generators can address this need. Recently, several successful rotating machinery projects demonstrated the practicality and feasibility of the technology using the high temperature superconducting BSCCO wire. With progress in manufacturing long continuous lengths of the superconducting YBCO coated conductors, addition improvement can be made to these superconducting devices. This paper will briefly address the prospects for employment of the YBCO coated conductors in future power machinery demonstrations.					
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validates the HIA concept, but also advances multiple technologies that can support future HTS machine designs utilizing the latest-generation superconductors such as the YBCO coated conductor. GE is also performing the conceptual design of a 5-MW HIA with a goal to meet the above-noted specific power ratio.

III. YBCO COATED CONDUCTORS

As mentioned, the YBCO coated conductors offer substantial advantages over the BSCCO tape used to date. As a result, many companies are switching to the production of YBCO tapes instead of the BSCCO tapes as implementation and scaling-up of the processing advances. In the U.S. the production of BSCCO has been completely halted with sales limited to existing stocks. The newer YBCO conductor provides “form, fit, and function” replacement to have a minimal impact on application usage. Table I provides a current comparison of the two conductors. Extensive notes are provided below the table to document and clarify the data.

Since YBCO coated conductors are now made reel-to-reel in hundreds of meter length, research and development needs to shift toward improving the properties of the conductor as determined by application requirements. Indeed, demonstration projects using the new YBCO conductor are a critical step to ensure proper assessment of these requirements. This does not mean that additional improvements to the basic conductor architecture are not necessary or possible; however, implementation of the conductor is necessary to ensure economic viability of the industry in the interim. In the discussion that follows, the topics of higher critical currents and lower ac losses are discussed as two such parameters.

A. Higher Currents

An important parameter for enabling superconducting generator operation at relatively higher temperatures and/or to allow a more compact winding is increasing the amount of current the HTS tape can carry. This is accomplished by improving the in-field performance of the critical current density (J_c) in the superconductor. This will in-turn increase the overall critical current density of the wire, the engineering current density (J_E). Alternatively, J_E can be increased by making the superconducting layer thicker, since this layer is only a fraction of the overall composite wire’s thickness [11] – [13]. Even though the requirements of stability and quench protection do not allow an unlimited increase of J_E with increasing J_c , further improvements in J_c over the present level is highly desirable.

Improvement in the J_c of the superconducting layer itself can be done by incorporating better magnetic flux pinning centers. Nanoparticles have been demonstrated as the best pinning centers to date and can be incorporated by a variety of methods [11], [14] – [20], being first demonstrated by Haugan et al.

COMPARISON OF BSCCO WIRE AND YBCO WIRE.

Property ^a	BSCCO (now) ^b	YBCO (now) ^b	YBCO (near term) ^c
Cost (relative) ^d	16-20	50-100	3-5 ^e
Operating Temp. (in-field) ^f	22 - 35 K	45 - 55 K ^g	60 - 70 K ^h
J_E - Eng. Current Density ⁱ 77 K, self-field	7 - 17 kA/cm ²	8 - 29 kA/cm ²	15 - 50 kA/cm ² ^j
J_E - Eng. Current Density ⁱ 65 K, 2.5T//c	negligible	2.5 - 8 kA/cm ² ^g	8 - 20 kA/cm ² ^j
Tensile Strain 77K	0.10 - 0.40%	0.30 - 0.45%	0.30 - 0.60% ^k
AC-tolerance	As is [9], [10]	Similar, better [9], [10]	Improved 5-10X
Length	Up to 1.5 km	Up to 600 m	1 - 1.5 km

^aBSCCO wire is a more developed technology and although properties could improve, YBCO wire is less mature and making rapid advances.

^bBased on manufacturer’s data sheets available at company website as of the writing of this paper. A higher property in one row may mean a lower property in another row. BSCCO data composite from American Superconductor Corp. and Sumitomo Electric, Inc.; YBCO data composite from American Superconductor Corp. and SuperPower, Inc.

^cProjected based on author’s assessment of feasibility of implementation of referenced data in next ~5 years.

^dRelative based on \$/kA-m, 77K, self-field figure of merit.

^eYBCO rapid price decline projection and improved properties over BSCCO resulted in discontinued production of BSCCO wire in U.S.

^fBased on temperature to maintain J_c at ~18,000 A/cm² in 1 - 3 T field perpendicular to face of tape.

^gDerived from b above and typical in-field performance of YBCO without added pinning centers.

^hDerived from b above and [6].

ⁱDefined as the current per total cross-section of the wire without insulation.

^jDerived from b above, typical YBCO performance, and [6]. This excludes recent high pinning results that can further increase J_c and therefore J_E since not likely to be implemented within 5 years time.

^kBased on b above, [7], and mechanical enhancement such as [8].

Recently, nanoparticulate pinning has provided over two orders of improvement to the J_c of YBCO at several tesla using a BaSnO₃ (BSO) nanoparticle [19], [20] which has unique pinning properties different than other additives such as BZO, Y₂BaCuO₅, Y₂O₃, etc. There is some initial success in transitioning the nanoparticle approach to industrial methods [21], but the full value of improvement in industry is yet to occur and deserves a focused effort to fully transition the technology to industrial processing methods.

Another potential avenue to incorporate these pinning centers by a variety of methods is the addition of minute amounts of deleterious elements. One example is minute doping by the incorporation of very minor additions ($\leq 1\%$ of Y) of typically deleterious rare earths into high quality YBa₂Cu₃O_{7- δ} thin films to provide improvement of the film’s in-field current density [18]. In the cited work, it was accomplished without optimization of the deposition

TABLE I

parameters. Instead of typical site substitution for Y, the deleterious rare earths seem to form nanoparticulates, explaining why the enhanced performance over standard rare earth substitutions by the preferred elements. This method lends itself more readily to the industrial processes.

B. Lower AC Losses

AC losses occur in the YBCO coated conductor due to the applied alternating magnetic fields in the generator, but also can experience the losses by applying ac currents. These losses are a composite result of eddy-currents in the stabilizer and substrate, but primarily due to loss in the superconducting layer (hysteresis loss) [22] – [28]. A ferromagnetic substrate can cause some additional minor losses as well. If the generator is high speed, such as typical airborne generators, coupling losses will become quite important also.

Successful incorporation of HTS conductor into this environment depends on the particular usage of the wire—in the field windings, the armature windings, or both. The particular environment in the generator dictates as beneficial or necessary the measures to be taken to reduce these losses. Since previous demonstrations of HTS machinery were done with BSCCO, only the field windings were considered due to BSCCO’s limited ability to handle ac losses. However, the YBCO coated conductor is more conducive to an ac-tolerant version. How tolerant remains to be seen.

Although the YBCO coated conductor experiences primarily a dc field in the field windings, asynchronous feed back is possible causing an increased cooling load to handle the losses. The losses can be reduced through shielding of the windings; however, the extra shielding is unnecessary if an ac-tolerant form of the YBCO coated conductor is made. The importance of this problem was evident in a Westinghouse generator project where excessive heating in the shield occurred due to load-induced varying fields [29] – [30].

The greater challenge, if not unconquerable, is having superconducting armature windings—an extremely severe ac loss environment. Even if this is ultimately impossible for high speed generators, it may not preclude lower speed motors and generators from being fully superconducting. Superconducting armatures are often considered developmentally since ac-tolerant conductor meeting this environment will readily meet other applications. At least as early as 1967 the large losses possible in the armature winding became obvious in a unsuccessful fully superconducting Dynatech generator [31].

The hysteresis loss in YBCO tapes can be reduced by dividing the superconducting layer into a large number of parallel filaments segregated by narrow resistive barriers [32]. Power loss per unit length in a superconducting tape exposed to magnetic field varying with frequency f is given by

$$Q_h \approx I_c W_n B_{\perp} f . \quad (1)$$

Here W_n is the width of an individual filament, B_{\perp} is the peak value of the magnetic field perpendicular to the wide face of the tape and I_c is the total critical current of the wire. Thus, hysteresis loss can be reduced in proportion to the number of

filaments. Measurement of the magnetization losses in experimental multifilamentary YBCO coated conductors made by laser ablation have been reported recently [33] – [40]. Indeed, the hysteresis loss, identified by its linear frequency dependence, has been reduced as expected. However, a new source of dissipation - coupling loss - has appeared in the multifilamentary samples and the loss was comparable to the hysteresis loss, even at relatively low values of the sweep rate $B_{\perp} f \approx 3 . T/s$. This problem was overcome by additional post-ablation treatment of the wires that improved the insulation of the filaments [41], [42]

This straightforward solution of the ac loss problem is not without issues. If the filaments are very fine, breakage could potentially become a serious concern. Since the individual filaments have to be well insulated from each other in order to prevent coupling loss, they cannot effectively share the supercurrent. Therefore, the entire length of a filament can be made unusable by just one defect. A solution to this problem has been found in a form of sparse network of superconducting bridges connecting the filaments [43], [44]. If the bridges are placed near the neutral line where the electric field induced by the time-varying magnetic field is minimal, the additional losses in the bridges are insignificant. Such “multiply connected” superconducting wire would be much more robust than a similarly striated conductor with filaments insulated along their entire length. A number of experiments have been carried out to measure the losses [36] – [39] and to clarify the details of current redistribution between the filaments in multiply connected coated conductors [45] – [47].

It should be noticed that all above mentioned experiments have been carried out on coated conductors without copper stabilization. Only a thin, few microns thick, silver layer was covering the YBCO film. A truly stabilized multifilament coated conductor will require the copper stabilizer to be striated in the same pattern as the underlying superconducting film; or conversely, that the applied copper stabilizing layer is only coated on the YBCO filaments separately.

SuperPower, Inc. has taken efforts recently to scale up the filamentary concept to reel-to-reel processing using lithography techniques [5]. This method strives to accomplish striation by segregating the filaments with narrow insulating grooves so as to minimize the amount of removed superconductor. Slitting to smaller widths than the standard 4 mm tapes has also been demonstrated. SuperPower has shown an ability to twist the YBCO coated conductor while maintaining at least 95% of the original critical current.

IV. LOSSES IN SUPERCONDUCTING ARMATURE

In this section we will consider simple back-of-envelope type estimates of losses in a superconducting armature of a generator. Figure 1 shows a sketch of a cylindrical “generator”. In cylindrical coordinates, the active lengths of the coils are extended in the z-direction perpendicular to the page.

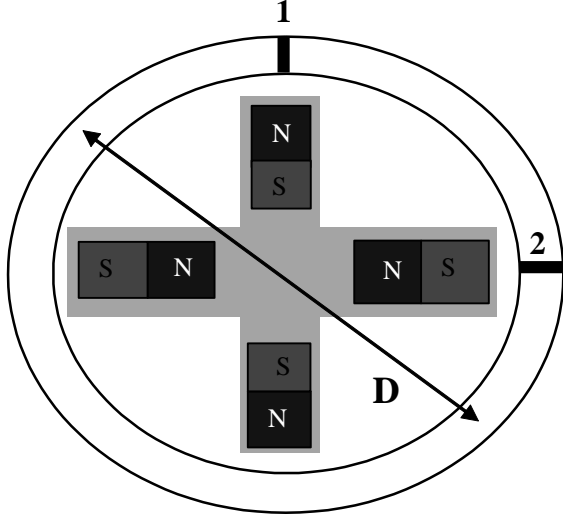


Fig. 1. A sketch of the cross-section of a 4-pole generator. The numbers 1 and 2 indicate the active lengths of a single loop in the armature extended in the z-direction. D is the average diameter of the armature.

Since the power output and the power loss in the armature are additive quantities, it is sufficient to consider power output and power loss in just one turn (loop) of one armature coil. From Maxwell equation $\nabla \times \vec{E} = -\dot{\vec{B}}$ it follows that the potential difference generated across the loop is

$$V = \partial\Phi / \partial t \quad (2)$$

where Φ is the time-varying magnetic flux passing through the loop. Assuming a single frequency harmonic time variation, the peak value of the potential is given by

$$V_p = \Phi_{\max} \omega. \quad (3)$$

Here ω is the angular frequency of the magnetic field variation and Φ_{\max} is the peak value of the magnetic flux. If p is the number of the rotor poles and f is the frequency of its rotation (in revolutions per second), then

$$\omega = \pi f p. \quad (4)$$

The peak value of the magnetic flux through the loop can be defined as follows:

$$\Phi_{\max} = B_r l l_{arc}. \quad (5)$$

B_r is the characteristic value of the radial component of the magnetic field (close to its peak value), l is the active length of the loop, and l_{arc} is the pole arc, which we will consider to be close to the pole pitch - the distance along the circumference

between the points 1 and 2 in Fig. 1. Thus

$$l_{arc} \approx \pi D / p,$$

and

$$V_p = \pi^2 B_r l D f. \quad (6)$$

The impedance of the load has to be sufficiently large to maintain the peak current in the superconducting loop below its critical current I_c . Let us take the peak current to be $I_p = I_c / \sqrt{2}$, which means that $I_{\text{rms}} = I_c / 2$. Then, the power output of a single loop is given by

$$P_{\text{output}} = \frac{1}{2} V_p I_p = \frac{\pi^2}{2\sqrt{2}} (B_r f) I_c D l \quad (7)$$

We can also estimate the hysteresis loss in the loop defined by Eq. (1). In the armature winding, the coated conductor has to be placed in the radial slots, so that the radial component of the magnetic flux density B_r is parallel to the wide face of the conductor and, therefore, does cause energy dissipation. The energy loss is caused by the azimuthal component B_ϕ , so that

$$Q_h \approx 2W_n (B_\phi f) I_c l \quad (8)$$

Here we have neglected the losses in the return path of the loop which is exposed to z-component of the magnetic field. Thus, a simple result follows - the hysteresis loss in the armature scales with the power output:

$$\frac{Q_h}{P_{\text{output}}} \approx \frac{4\sqrt{2}}{\pi^2} \frac{B_\phi}{B_r} \frac{W_n}{D} \approx 0.6 \frac{B_\phi}{B_r} \frac{W_n}{D}. \quad (9)$$

The output power and the total hysteresis loss are additive quantities, so that Eq. (9) describes the ratio of the total hysteresis loss in the armature to the total output of the generator. The ratio is independent of frequency and the number of poles because the hysteresis loss and power output scale with frequency. For other components of losses this is not true. Here, however, we assume that the hysteresis loss is the dominant component and presents the main problem.

The condition of reduction of the armature hysteresis loss relative to the output power favors large diameter machines. This conclusion seems rather ironic because one of the main incentives to consider the all-superconducting generator is the prospect of its size reduction. As was mentioned in section II, an initial goal for specific power ratio of an HTS generator is 8.8 kW/kg. This translates to the total mass of 114 kg per 1 MW output. Let us assume, for the sake of argument, that the weight of the cryocooler for such a generator should not

exceed 10% of its total mass. Therefore, in this example, the cryocooler mass should not exceed 11.4 kg per 1 MW of the generator output. Mass of a cryocooler per unit input power is currently estimated as 11 kg/kW. Thus, the input power of the cryocooler servicing our hypothetical generator should not exceed 1kW per 1 MW of the generator output. The efficiency of the cryocoolers at an operating temperature of 65 - 70 K is

$$\eta \approx 30. \quad (10)$$

This means that 30 W of input power is required to lift 1 W of heat from the cold space. Thus, the amount of power loss in the armature should not exceed 33 W per 1 MW of the generator output. Using this figure, we obtain from Eq. (9) the following restriction on the width of the filaments:

$$\frac{B_\phi}{B_r} \frac{W_n}{D} \approx 0.5 \times 10^{-4} \quad (11)$$

Let us assume first that the peak values of the azimuthal and radial components of the magnetic field are close to each other in the volume occupied by the armature. In order to satisfy the condition (11) for a beer-keg sized generator with the diameter of the armature $D = 50 \text{ cm}$ (20 in.) the width of an individual superconducting filament should be $W_n \approx 25 \mu\text{m}$.

V. CONCLUSION

YBCO coated conductors are now available in lengths sufficient for rotating machinery demonstration projects. Besides being an improved HTS wire over the previous generation BSCCO wire, it is also projected to be cheaper making it more economically viable. Current properties of the YBCO superconducting wire were presented for currently available tapes as well as projection for the next 5 years. Additional development that the YBCO wire should undergo to fully exploit its capability was also briefly discussed.

As a final example of a possible development goal for the YBCO conductor, especially with respect to ac loss minimization, the width of filamentation in an ac-tolerant version of the tape was discussed. Reaching thin widths such as 25 μm is not entirely implausible, but is certainly a very difficult task. Most experiments that were cited in this article were carried out on YBCO coated conductors with 500 μm wide filaments. 400 stripes per cm width is an optical grating quality and the technology of coated conductors is not clearly near this capability. This may also suggest that if superconducting windings are to be expanded in use from the field windings to the armature windings as well, it may only be possible in large, lower-speed generators such as for the Navy electric ship drive.

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VII. BIOGRAPHIES



Paul N. Barnes is a principal research physicist and the Research Group Leader for the Power Generation Branch of the Air Force Research Laboratory (AFRL). The group includes high temperature superconductivity (HTS), magnetic materials, carbon nanotubes, and dielectric insulation research. His research group also oversees several contractual development programs. Dr. Barnes received his PhD in Physics from the University of Illinois at Urbana-Champaign. He has authored or co-authored over 100 papers. His superconductivity group has been awarded Star Team Status by the Office of Scientific Research and he has received the Heron Award, named Scientist of the Year and named as an AFRL Fellow. He also serves on several boards and committees for superconductors and cryogenic materials.



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