

Design of Compact, Lightweight Power Transmission Devices for Specialized High Power Applications

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ABSTRACT

The design of compact and lightweight power transmission devices was studied for specialized high power applications, including airborne with operating voltage fixed at 270 Volts and less than 30 meter length conductors. Only commercial-off-the-shelf components were considered for the design. It was found that by using superconducting wires operated at cryogenic temperatures instead of Cu conductors, a large increase of performance could be achieved; e.g. there is large reduction of heat loss; and for 5 MW-class or 20 kA power transmission there is a substantial reduction of weight of ~ 80/kg per meter and an approximate 10x reduction of volume. A strong reduction of weight is achieved for > 1000 Amp power transmission.

INTRODUCTION

The development of new electric conductors in the past 20 years with up to 200x higher power/volume capacity than standard copper conductors has created the potential to use these new conductors to improve the performance and efficiency of high-power current transmission systems. New materials with higher conductivity include doped carbon graphite or nanotubes, hyperconducting metal alloys, or advanced high temperature superconductors (HTS) with operation temperatures up to 80 K¹.

The development of improved power density devices for specialized applications including airborne is on-going²; however, the problems of electrical power transmission between these devices still need consideration. For example, the weight of power cables running from advanced airborne high-power generators is likely to exceed the generator weight, and heat losses of wires which are proportional to the increased device power levels can reduce system performance. To further improve high power device operation at 50 K to 300 K, the design and optimization of power transmission devices can reduce system heat loss and weight. While development proceeds on higher performance power transmission devices for commercial power industries³⁻⁵, relatively little effort exists for optimizing the power transmission systems for low voltage operation and low

AC frequency or DC systems typical for many specialized high power applications. Previously development of superconducting power lines for high voltage, high power operation (20-120 kV, 100-1500 MW) demonstrated 4-40x reduction of total system heat loss (including cryogenic) and an approximate 10x reduction of transmission cable size and weight compared to copper, for commercially viable systems³.

Herein considers the design of electrical power transmission systems for specialized applications such as airborne. The basic research principles to study this problem have been well-established, as will be shown. However airborne applications have specific design criteria which have not always been considered in detail yet. For airborne applications, the operating voltage is typically fixed at $V = 270$ Volts because of many considerations including the need to minimize arc discharges at lower atmospheric pressures. It might be possible to engineer around this requirement with increased electrical insulation, however this possibility was not considered herein.

The output or operating power of a device is known from basic principles and Ohm's law as $P = IV$, where I is the current applied and V is the operating voltage. Therefore, to increase the power output substantially for airborne applications it is not practical to increase the operating voltage as is common for ground-based transmission systems, but only the operating current must be increased. This benefits device design by reducing the amount of electrical insulation, however causes different design problems to accommodate higher currents.

This paper studies the design of high power transmission lines and cryogenic current leads for low voltage (< 300 V) and DC or low-frequency AC (< 1000 Hz), and also short length < 30 meters which are useful for airborne applications. Although designing for any operation temperature can be considered, the emphasis herein is for operation temperatures of 50-80 K for compatibility with next-generation high-power applications including generators utilizing YBCO high temperature superconductor (HTS) wires^{2,6}. The design of a system that demonstrates competitive system size, weight

and/or power loss reduction is a goal. For any high-power application, the development of refrigerated (or cryogenic) power transmission systems has potential if the system size, weight and power losses including refrigeration can be lower than comparable room-temperature copper or aluminum and solid-state components.

Preliminary results herein show that by using new generation high-temperature superconducting wire, similar reductions to high-voltage commercial-power systems can be realized for 5MW-class power transmission, giving substantial weight reductions of about 80 kg/m of wire compared to copper. Reduced power losses also are achieved, however the savings in weight is comparatively more substantial.

LONG LENGTH CONDUCTORS

While research and development of higher conductivity materials is on-going, there are relatively few conductor materials that have been successfully manufactured in long lengths ~ 0.5 -1.0 km with reasonable cost and physical properties sufficient for commercial sales¹. Wire manufacturing lengths ~ 1 km are needed, to assemble higher current cables carrying 10kA or higher of 10-30 meter length.

Figure 1 compares commercially available 400A-class Cu transmission wires that operate at-or-near room temperature to $\text{YBa}_2\text{Cu}_3\text{O}_{7-z}$ (YBCO) high temperature superconductor (HTS) wires that operate at 4-80 K. The YBCO wire is approximately 800x smaller in volume and weight than Cu, while carrying the same 400 A however at 77 K rather than room temperature. The equivalency is based on YBCO wires carrying critical current (I_c) = 1000 A/cm which have been achieved in short processing lengths of ~ 1 meter. Although improvements are rapidly being made, the performance of YBCO wires at the present state of manufacturing development goes down from this for longer length processing of ~ 950 m with $I_c = 200\text{A/cm}$, as shown in Fig. 2. Depending on the operation temperature and magnetic field, Fig. 2 shows that YBCO conductors processed in km lengths has higher current density compared to other conductors in fully engineered and manufactured conductors. Operation of YBCO wires at 77K for most applications is technologically achievable by using relatively small cryocoolers, as will be shown herein.

Operation of Cu wires at cryogenic temperatures is not practical for long durations, because the power loss from resistive heating with cryocooler inefficiency is too large a percentage of the power transported. In contrast the electrical resistance and power loss of YBCO wires at $< 80\text{K}$ is practically zero for DC current transmission, so the only power loss for the transmission system is the cryocooler and vacuum component losses needed to maintain the cryogenic environment⁴.

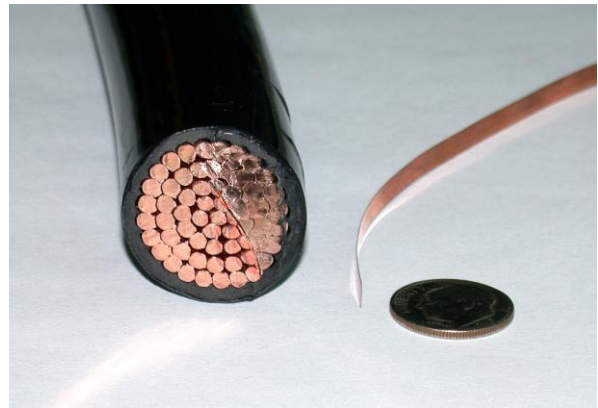


Figure 1. Commercially available 400A-class wires of Cu (left) and $\text{YBa}_2\text{Cu}_3\text{O}_{7-z}$ (YBCO) middle (at 77K operation temperature), compared in size to a dime. Interestingly, the superconducting volume of the YBCO wire which is $\sim 0.4\text{cm} \times 0.01\text{cm}$ is $\sim 1\%$ of the volume shown, with the balance being ~ 0.005 cm thick metal-alloy substrate and ~ 0.005 cm thick copper layer for stabilization in case of quench. The volume and weight of this Cu wire compared to YBCO is $\sim 800:1$, and the ratio for comparing multiple 2/0 Cu wires with 400 A capacity to YBCO is $\sim 400:1$.

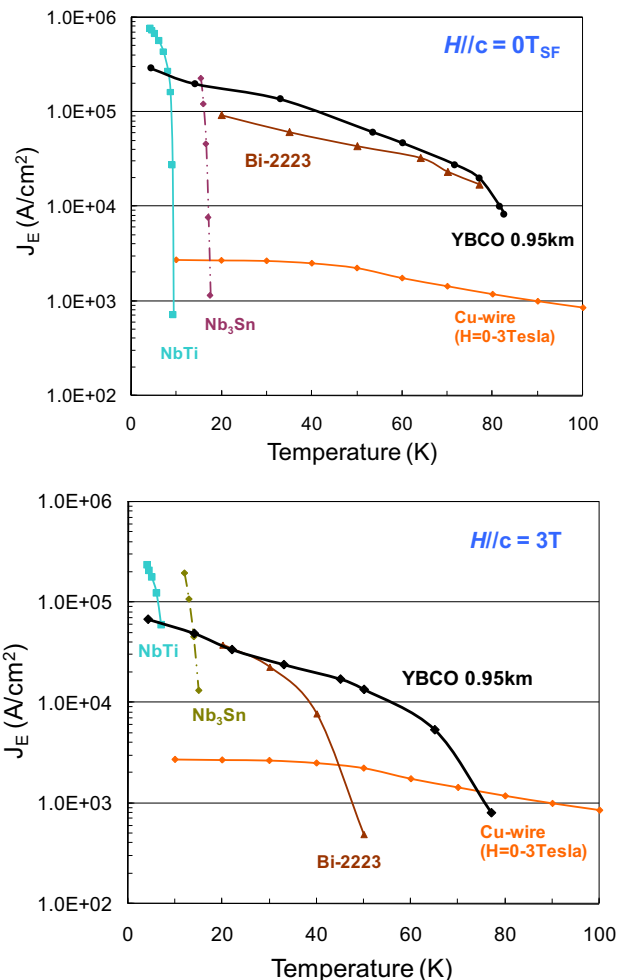


Figure 2. Engineering current density of km-length commercially available superconductors wires,
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compared to standard Cu wires that function in self or high magnetic fields⁷⁻¹⁰. The dependence on temperature is shown, for applied fields in the worst orientation of H//c-axis with magnitudes of 0 Tesla (self-field) which is used for power transmission, and 3 Tesla which is typical for many power applications. Superconductors are low temperature NbTi and Nb₃Sn, and high temperature YBa₂Cu₃O_{7-z} (YBCO) and (Bi,Pb)Sr₂Ca₂Cu₃O_{10-z} (Bi-2223). The quality of YBCO manufacturing is continually improving, and the J_e values are shown as of July 2008.

SYSTEM THERMAL HEAT LOSS

The system thermal heat loss (Q_s) of an electrical power transmission system depends on a number of components, and can be written as

$$Q_s = \xi_{CR} * (Q_{CD} + Q_{VT} + Q_{CL}), \quad (1)$$

where ξ_{CR} is the efficiency of the cryocooler if used, Q_{CD} is the heat loss of the conductor, Q_{VT} is the heat loss of the vacuum tubing if used, and Q_{CL} is the heat loss of the current leads into and out of the power transmission system which can be significant if the system is operated at refrigerated temperatures.

In the following sections, the specific heat losses are described in detail.

POWER LOSS OF CONDUCTORS – The power loss of the conductors are described in the following.

Power Loss of Resistive Conductor - The power loss of resistive conductors such as copper or aluminum is known from Ohm's law as

$$Q_{CD} = P = I^2 R \quad (2)$$

where $R = \rho L/A$ is the resistance of the conductor, with ρ = resistivity, L = wire length, and A = wire cross-sectional area. The square dependence on current creates additional problems for airborne applications, and suggests there is a need to greatly reduce R as much as possible to minimize heat losses. The only alternative to reducing the resistance is to reduce the operation time to reduce the energy loss for a given time. The resistance of copper cables of different designs including Litz wire for AC operation are quantified by commercial manufacturers, and are freely available¹¹.

Power Loss of Superconducting Cables: AC - The power loss of superconducting cables for AC transmission has been studied in great detail, and the principles to reduce and control heat losses are understood from theory and modeling¹²⁻¹⁶. A critical factor to lower AC loss is to reduce exposing the tape to perpendicular magnetic field components as much as possible, which has a much larger effect than parallel magnetic fields¹². The AC power loss can be reduced to very low levels by considering and optimizing cable geometries, and by reducing operation temperature and filament width. In general, as the current level increases

the cable size must increase significantly to minimize exposing individual conductors to perpendicular magnetic fields. Figure 3 plots both measured and theoretical AC losses for different cable designs. It is seen in Fig. 3 that to increase the currents from 1kArms to 10kArms and keep losses < 1 W/m, the diameter of the cable should be increased from ~ 2 cm to ~ 9 cm. Each AC wire design has particular parameters that change the dependence, however in general the cable diameter must be increased with current capacity to keep AC losses at very low levels such < 1 W/m.

Also Fig. 3 shows that for a given design, the heat loss generally grows exponentially with increasing current above the designed-for current.

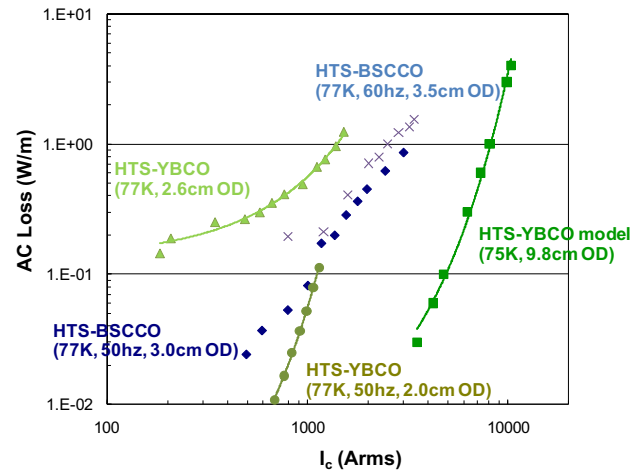


Figure 3. AC loss of high-temperature-superconductor cables: ● Amemiya¹² ▲ Gouge¹⁴ ■ Rastila¹⁶ ◆ Kimura¹³ and x Sytnikov¹⁵. Lines shown are exponential fits.

Power Loss of Superconducting Cables: DC - The design of high current superconducting cables for DC transmission is simpler than for AC transmission, however also depends on geometrical factors to minimize reduction of I_c from self-field magnetic effects⁴. Not accounting for self-field reductions or losses from harmonics which can be important for ground-based long length power transmission⁵, the DC loss is calculated with the simple formula $P = IV$ and rewriting using the electric field

$$P = IV = IEL \quad (3)$$

where I is the current, E is the electric field, and L is the wire length. The electric field of YBCO HTS coated conductor wires is shown in Table I, which shows very low electric field until the current exceeds the 'critical current' value defined roughly using the criteria of $E = 1 \mu V/cm$. Table I shows that it is possible to operate HTS wires with almost immeasurably low electric fields even in magnetic fields, and therefore the power loss calculated from Eqn. 3 is very low even with very high currents or long wire lengths. As an example, for high power applications with $I = 20$ kA and $L = 10$ meters, the power loss can be reduced below 10^{-3} Watts by choosing the correct operation current. So for most practical