The Application of High Temperature Superconductors to Space Electrical Power Distribution Components

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TO SPACE ELECTRICAL POWER DISTRIBUTION COMPONENTS

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SUMMARY

The recent discovery of a class of high temperature superconducting (HTS) ceramics which remain superconducting at temperatures near 125 K has stimulated the terrestrial electric power industry to take a new look at the impact superconductors could have on the generation, storage, and distribution of electric power. It is equally important that the space electric power community ask the same questions and examine its systems and components to determine what could be achieved by the introduction of HTS into its technology. This is especially important, because for a low loss system it may be possible to achieve superconductivity at temperatures near 125 K with only passive cooling, where it is essentially impossible to achieve traditional superconducting temperatures (~15 K) without a major mechanical refrigeration system or the use of liquid helium. The potential for impact derives from the ability of superconductors to carry electric current without loss as long as they are maintained at a low enough temperature, magnetic field, and current. The realization of their potential, of course, depends not only on the values of the above parameters but on more mundane, but crucial questions such as their fabricability, availability, stability, cost, weight, etc. The values of these parameters and the answers to the questions are, as yet, inadequately known and are the subject of intensive research.

This paper will examine some important space based electrical power distribution systems and components and compare the pre-HTS state-of-the-art with what might be achieved with the introduction of HTS. Components to be compared will include transformers (present weight of high frequency power transformers is about 0.2 kg/kW at 20 KVA), capacitors (at 40 kHZ and 0.05 kg/kVA), and transmission lines where the expected current density could increase two orders of magnitude from perhaps 100 A/cm^2 to 20 000 A/cm^2. It was concluded that the primary gain from HTS in larger space systems will be in HTS use as transmission lines, rather than in transformers or capacitors.

INTRODUCTION

In 1986, a new class of superconductors (HTS) were discovered. They are ceramic compounds, based on the copper oxides, which exhibit zero electrical resistance at temperatures (T_c) as high as 125 K. This development was a surprise to the scientific community which, for the most part, was convinced that nature would not allow T_c to exceed 30 K. The sudden jump of T_c from 23 K to well above liquid nitrogen temperatures (77 K) requires that a new look be taken at the practical application of the phenomenon. Liquid nitrogen is a

coolant which is ubiquitous in our technology and is less apt to be an impediment to large scale application than liquid helium. More exciting is the possibility that even higher temperatures, i.e., room temperatures, may be just around the corner.

Space electrical power systems are particularly appropriate for early power applications of HTS. In such systems weight/performance is a dominant figure of merit. It is expensive to launch mass and therefore conductor systems which, because of their high cost/performance may not be attractive for terrestrial use, may be conductors of choice for space. Further, for many space applications 77 K is "room temperature" (i.e., only passive cooling may be required).

Space power systems tend to be unique to the mission they serve. Therefore we will not consider a "designed from the ground up" HTS power system. Instead we will look at the implications of replacing the normal conductor in three important and ubiquitous power system components with HTS, i.e., transmission lines, transformers, and capacitors. State-of-the-art components will be described and extrapolations will be made to component characteristics expected using HTS. This exercise presupposes the development of a practical conductor technology, such as flexible ceramic woven fiber or thin film sheet conductors and may help guide the development of appropriate conductors. Passive cooling by radiation to space is the only cooling assumed although the penalties and benefits of active cooling are easily seen.

TRANSMISSION LINES

Components in this category range from straight forward point-to-point wiring on a spacecraft to kilometer long self supporting cables connecting a remote power source such as a nuclear reactor, to an inhabited space coloiy. The tradeoffs can be quite different in the two cases. In this paper we will consider the simple case of point-to-point wiring.

The transmission line losses and the associated weight penalty have been treated previously in references 1 to 3 where considerable attention has been given to the problem of disposing of the waste heat.

The weight penalty (W_p) is composed of three parts. First is the weight (W_{t1}) of the line itself which is assumed to be entirely conductor. Second is the weight (W_{ps}) of the added power supply to make up for the losses and third the mass of any added radiator to dispose of the heat. We will neglect this contribution by staying in the regime, for normal conductors (j_c = 200 A/cm^2), where this weight is small.

Hence,

$$W_p = W_{t1} + W_{ps} \tag{1}$$

and,

$$W_{t1} = 2ALd \tag{2}$$

where A is the cross-sectional area of the wire, L is the length of the line, and d is the density of the conductor material. Also,

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$$W_{ps} = aI^2\left(2\rho\,\frac{L}{A}\right) \tag{3}$$

where I is the current, a is the inverse specific power (wt/power), and ρ is the resistivity of the conductor.

Combining the above equations we can write

$$W_p = 2AL\left(d + a\rho j_c^2\right) \tag{4}$$

If we put in values of d and ρ for copper (8.9 gm/cc and 1.6×10^{-6} Ω cm) and take a reasonable value (ref. 4) for a, i.e., 250 gm/W, it is clear that for $j_c = 100$ A/cm^2 the additional power supply is a significant fraction of the weight penalty.

We now calculate A in terms of the total power (P) and the system voltage (V).

$$A = \frac{P}{j_c V} \tag{5}$$

Therefore,

$$W_p = 2LP\left(\frac{d + a\rho j_c}{j_c^2 V}\right) \tag{6}$$

For HTS lines, the second term is neglected ($\rho = 0$) and if $j_c = 2\times10^4$ A/cm^2 (a value typical of the present generation of commercial superconductors) we find that the weight penalty is reduced by a factor of 0.0034.

Setting the operating voltage (V) to 200 V, yields

$$\frac{W_p}{LP} = 1.3\times10^{-3} \text{ gm/cm-W} \tag{7}$$

Therefore a single 100-m line (pair) contributes about 13 kg/kW. However this neglects an important point. Power management and redundancy requirements, such as in Space Station (private communication from J. DePauw), can raise the weight penalty by an order of magnitude to 130 kg/kW.

TRANSFORMERS

HTS, though they are lossless when used with dc, do exhibit losses when exposed to ac. These losses are associated with flux pinning in the superconductor and currents that flow in the normal material used as thermal, mechanical, and electrical stabilization. This is a complex technical issue (ref. 5)

however the losses (dQ/dt), which are proportional to the frequency (f) and the square of the p-p amplitude of the ac magnetic field (B), can be summarized as follows:

$$\frac{dQ}{dt} \propto B^2 f D(s,\rho,g,j_c,f) \tag{8}$$

where D is a loss function which depends on conductor and filament dimensions (s), geometry (g), resistivity (ρ), critical current (j_c), and frequency (f). These losses have been maintained well below those of normal conductors in various ac applications up to around 100 Hz however significantly higher frequencies will be a technical challenge. Table I describes the weight breakdown for a 25 kVA, 20 KHz transformer designed for space (ref. 6). The conductor is about 28 percent of the total weight of the device and is assumed to work at a current density of 200 A/cm^2. Since we have seen that HTS current densities are at least 100x higher it is clear that most of the conductor weight could be eliminated. It might be possible, in addition, to reduce, as a result, some of the structure. Therefore, nearly 28 percent of the weight of a space power transformer could be eliminated by the introduction of HTS, a reduction in weight to about 0.1 kg/kW. The biggest impact, however, might be the elimination of this class of device by exploiting the zero loss and high current densities of HTS to go to dc distribution.

HIGH POWER CAPACITORS

Capacitor applications fall into two categories. They may be chosen for high power or for high energy density. The two are related by the frequency.

$$\text{power/weight} = f \times \text{energy/weight} \tag{9}$$

State-of-the-art in power capacitors is about 0.05 to 0.1 kg/kVA at 20 to 40 kVA (ref. 7 and 8). For example; a 75 kVA, 600 V, 125 A, 40 kHz polypropylene capacitor weighs 3.2 kg and exhibits a loss of 22 W, or 0.03 percent. Some of this was dielectric losses and the rest could be attributed to a series resistance of about 0.001 Ω. HTS would reduce this still further but it is clear that direct replacement of the conductor in a capacitor with HTS will have little impact on the weight (table II). As in the case of the transformer, the major impact of HTS on the weight of a space electric power system is apt to come from the elimination of capacitors by a redesign of the power system.

CONCLUSIONS/SUMMARY

From the preceding rather cursory look the following conclusions can be drawn.

1. HTS has its greatest effect on the weight associated with transmission lines. Their large j_c allows a reduction of about 300x in the weight of the wiring. This could amount to as much as 130 kg/kW for a kilometer of cable or 1300 kg/kW if system redundancies are included.

2. Transformers, because only 28 percent of their mass is in the conductor, are reduced in weight by the same factor.

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3. Capacitors are helped the least and only negligible savings are possible in their individual weights.

4. A major driver for the use of ac in high-power resistive systems in space is the need to reduce conductor mass. Because of their large j_c, HTS can relax the requirement to go to ac and thereby can generate significant savings by eliminating most transformers and capacitors.

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TABLE I. - 25 kVA TRANSFORMER WEIGHT BREAKDOWN

[Specific weight = 0.13 kg/kVA.]

	Weight, kg	Percent total weight
Magnetic core	0.70	22.0
Coils and buss bar	.87	27.6
Structure	1.14	36.0
Insulators	.21	6.8
Fasteners	.24	7.6
Total	3.16	100

TABLE II. - POWER CAPACITOR WEIGHT BREAKDOWN

	Weight, kg	Percent total weight
Conductor	0.20	6.25
Dielectric	.60	18.75
Structure/Case	2.40	75.0

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