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LIGHTWEIGHT POWER BUS FOR A BASELOAD NUCLEAR REACTOR IN SPACE

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ABSTRACT

Space environmental interactions with the power distribution/power processing subsystem can become a serious problem for power systems rated at 10's to 100's of kilowatts. Utilization of ceramic superconductors at 1000 A/cm^2, which has already been demonstrated at 77 K in a conductor configuration may eliminate both bus mass and distribution voltage problems in a high power satellite. The analytical results presented here demonstrate that a superconducting coaxial power transmission bus offers significant benefits in reduced distribution voltage and mass.

Introduction

Baseload satellite power requirements in the range of 10's to 100's of kilowatts will potentially require a nuclear reactor with a long boom between the energy conversion subsystem and the load. As the power level from the space nuclear reactor power system increases, voltage, current, or both will have to increase dramatically beyond conventional practice. New approaches will be required to provide the power transmission bus between the nuclear reactor and the load.

Environmental and induced interactions with the power distribution/power processing subsystem may be the least understood and most serious obstacle to deploying and operating a space platform with high power consumption (hundreds of kilowatts/megawatts). Figure 1 shows the nature of the problem in terms of the effects of the space plasma environment on exposed conductors. Higher power requirements force the spacecraft power system to higher voltage to keep conventional bus conductor losses low.

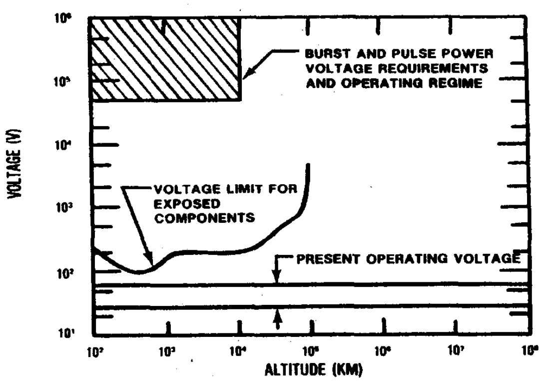

FIGURE 1. EFFECTS OF PLASMA ON EXPOSED HIGH VOLTAGE COMPONENTS[1]

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Present spacecraft have solar power requirements ranging from hundreds of watts to several kilowatts. Power is generated at 28 V and the distributed currents are of the order of 100 A or less. The Space Shuttle can provide up to 12 kW of power from three on-board hydrogen-oxygen fuel cells, which is distributed at 28 V, and the distributed currents are of the order of hundreds of amperes. For future specialized baseloads, hundreds of kilowatts may be required and it is likely that space nuclear reactor power systems will be necessary. Efficient transmission at these power levels will require either much higher distribution voltages (several hundred volts to a kilovolt or more) or a low-loss superconducting coaxial power transmission scheme. Higher distribution voltages impose very difficult conditions on the bus dielectric.

Low Loss Transmission Lines

The alternative approach addressed in this paper is to use high temperature superconductor power transmission at low voltage to achieve lossless transmission and minimize the need for down stream power conditioning. The power is transmitted at the primary generation/utilization voltage (28 V DC) by high temperature superconductors cooled to liquid nitrogen or liquid hydrogen temperatures. This low voltage distribution system will eliminate most of the problems associated with dielectric insulation degradation due to atomic oxygen in low earth orbit[2,3].

Redundancy in a low loss transmission bus can be provided by incorporating several sealed conductors within a single insulating sheath (Figure 2). These designs and techniques have been applied to high voltage transmission lines in three recent preliminary reports from NASA Lewis Research Center[4-6]. Figure 2 and Table I have been extracted from these reports. An external shield shown in Figure 3 protects the transmission line from thermal input from the ambient space environment and meteoroid impacts which could cause a loss of coolant (or SF_6 in the case of high voltage enclosures).

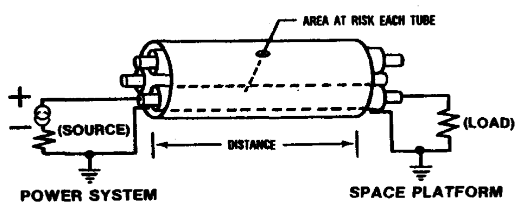

FIGURE 2. SOURCE TO LOAD CONNECTION WITH COAXIAL TUBES[4]

TABLE 1

SPACE TRANSMISSION LINE[4]

	LINE A	LINE B
TRANSMISSION LINE LENGTH	3km	3km
POWER LEVEL	.3MWe	.3MWe
PERCENT POWER LOSS ALLOWED	1.5%	1.5%
VOLTAGE	6.1kV	9.8kV
DIMENSIONS(mm)		
TUBE OD	17.7	11.3
ID	16.6	10.6
TRANSMISSION LINE MASS	1937.1kg	968.5kg

For high temperature superconductor power transmission, terminations and feedthroughs would also be problems that would have to be addressed and solved just as in the case of high voltage power transmission lines. Special precautions would have to be taken in the high temperature/high radiation environment near the space nuclear reactor source. In terms of construction, need for enclosures, and meteoroid protection, the high temperature superconductor transmission line is similar to the technical challenges of an SF_6 enclosed high voltage transmission line.

A space power bus which connects a baseload nuclear reactor to the load will generally be low voltage and of 10 to 100 meters in length. Because power levels will generally remain in the 10 to 1000 kW range, currents will only be 100 to 10,000 amperes, and ultrahigh current densities will not be required. It is possible, therefore, to quickly demonstrate the utility of high temperature superconductors for low power satellites (less than 100 kW) where distribution voltage is of great concern because of the space environment.

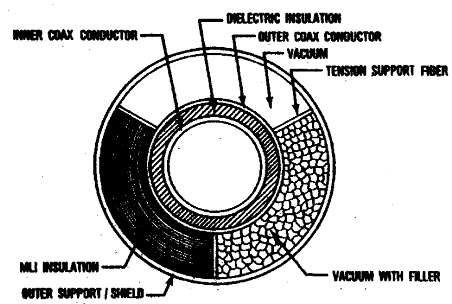

FIGURE 3. ELEMENTS COMPRISING A CERAMIC SUPERCONDUCTOR TRANSMISSION BUS FOR SATELLITE APPLICATIONS. THREE ALTERNATIVE METHODS PROVIDING THERMAL INSULATION ARE SHOWN

Current satellite systems are being pressed to higher and higher voltages because distribution conductors run hot and distribution voltage drop is high. Nearly all voltage requirements above 28 V_{dc} are caused by power distribution losses. Operation of new ceramic superconductors at temperatures greater than 70 K would permit low refrigeration losses and moderate current density in the range of 100 to 1000 A/cm^2. Because of the low magnetic field induced by the low electrical currents, it is possible to conceive applications of ceramic superconductors as they exist today. The following analysis assumes that long ceramic superconductors can be successfully fabricated at current densities near 1000 A/cm^2 in very low magnetic fields (less than 0.1 Tesla).

This paper will describe the range of application of high temperature superconductors to low power satellites, with special emphasis on the design of a satellite power distribution system at low voltage for a low power spacecraft.

Methods/Results

A parametric analysis has been performed that determines the trade-off between superconductors operating at various current densities and conventional "hot" conductors operating at their maximum capabilities. The effect of pressing the "hot" conductors to higher power service causes conductor mass to increase at a fixed bus voltage. In order to minimize mass, the space power system designer is forced to generate a higher bus voltage to minimize mass as shown in Figure 4. Satellite power system designers are averse to bus voltages that exceed 100 V because of the environmental degradation of the dielectric insulation on the bus, although high bus voltage will significantly decrease the bus mass as shown in Table I[4].

The calculated transmission bus masses shown in Figure 4 are based on non-redundant coaxial conductors for simplicity. The conductor configuration cross section shown in Figure 3 illustrates a ceramic superconductor power transmission bus. The core of the coaxial line is hollow to allow refrigerant to be slowly circulated inside the tube to maintain the superconductor at the desired operating temperature. The coaxial bus itself is created around a ceramic dielectric insulator tube which has been processed so that ceramic superconducting layers are provided inside and outside the dielectric tube. The outer cylinder is fabricated from a lightweight, high-strength material such as hard rod polymer film to act as a shield against space debris and thermal radiation. The outer shield cylinder provides a vacuum space to minimize conduction and convection thermal losses. The coaxial conductor is assumed to be supported from the outer shield tube by very thin hard rod polymer tension fibers of minimal mass.

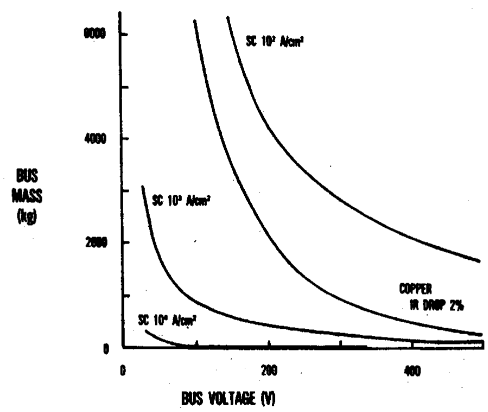

FIGURE 4. BUS VOLTAGE EFFECTS ON MASS FOR COPPER AND SUPERCONDUCTOR (SC) ON A 90-M BUS AT 250 KW

In order to limit refrigeration penalties, the sidewall thermal losses are minimized for various thermal conditions that may exist for the power bus. As an example, Figure 5 shows a typical baseload nuclear reactor configuration where the first meter of bus length may be subject to very hot temperatures near the reactor (up to 800 K) which is connected to a longer region which is subject to the ambient temperature of the backside of thermal radiators (we have assumed this region at 300 K) and finally an even longer region of bus that is largely subject to deep space temperature (as low as 100 K). Each of these regions will require different treatment of the vacuum space to minimize the thermal loss through the wall of the conductor. Figure 3 shows three approaches to the vacuum space which include: 1) vacuum with no filler, 2) partially filled space with foam or powder, and 3) superinsulation. Sittig[7] points out that temperatures of 1200 K can be withstood by superinsulation or multi layer insulation (MLI). For space applications, the MLI system is an order of magnitude less mass for the same insulation value as partially filled vacuum systems. The analyses in this report have been limited to the optimization of the power transmission bus using the MLI approach developed by Sittig[7].

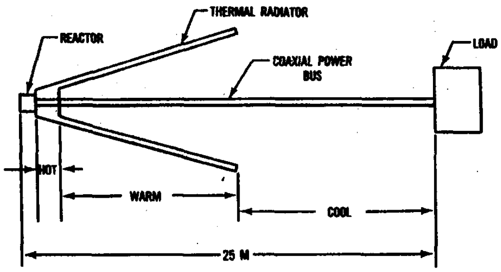

FIGURE 5. A TYPICAL NUCLEAR REACTOR DESIGN EMPLOYING THERMOELECTRIC LOW VOLTAGE ENERGY CONVERSION ELEMENTS AND A POWER TRANSMISSION BUS TO THE LOAD

For selected voltages, current densities, and power levels, mass and thermal loss calculations were performed to yield plots of bus linear density vs. ceramic superconductor current density as shown in Figure 6. Even at today's demonstrated current densities near 1000 A/cm^2, reasonable bus mass is achieved at zero voltage drop along the bus. A load voltage of 28 V_{dc} is assumed for all these calculations. The dramatic improvement in bus weight at higher current density in the range of 10^4 to 10^5 A/cm^2 which is available in metallic superconductors is apparant in Figure 6. As the baseload nuclear power level increases, the impact of high current density superconductors on mass reduction becomes more dramatic.

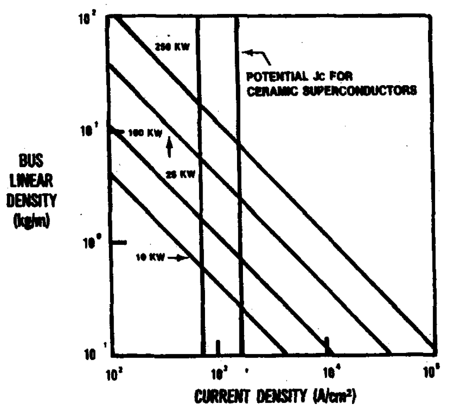

FIGURE 6. SUPERCONDUCTOR BUS MASS AT VARIOUS POWER LEVELS

Thermal Insulation And Refrigeration

Analyses of refrigeration power and mass of the refrigerator for the superconducting bus are progressing. The operating temperature of the superconductor and the local environment temperature are considered as variables. The superconducting bus will be subject to different load temperatures along its length between the baseload reactor and the load.

It can be of benefit to tailor the superconductor current density and operating temperature to minimize the system mass, which includes the refrigeration considerations. The effect of higher temperatures at the reactor on the power bus refrigerator must be analyzed and effective thermal insulation measures taken. The complete system mass optimization has not been accomplished yet where refrigeration mass is considered.

Most applications of the superconducting satellite transmission bus will produce a significant heat load at the termination points. Since temperature differences will be much smaller at the load end, few satellite applications will exceed one watt of thermal loss at the load termination. Since a reactor termination can be much hotter, this termination thermal loss can easily exceed one watt, but is unlikely to exceed 10 watts.

The main refrigerator heat load is strongly affected by the operating temperature range of the outer shield and the coaxial conductor. For the purposes of this study, low temperature differences associated with space temperature equilibrium are assumed to have one layer of MLI (although none would be required). Exterior shield wall temperatures of 300 Kelvin are assumed to require 8 layers of MLI and high temperature reactor locations are assumed to require 100 layers of MLI. The thick layers of MLI associated with high temperature differences will affect the overall bus diameter as shown in Figure 7, where the radius of all dimensionally significant elements shown in Figure 3 have been plotted. The high temperature bus will suffer a significant size penalty below 50 kW power levels. The calculation methods utilized in these analyses were taken from Kaganer[8] and do not include an outgassing correction for high temperature operation of MLI. The cumulative mass components of a 100 kW bus at 10^4 A/cm2 are plotted in Figure 8 to show that temperatures of several hundred Kelvin can be tolerated (20 to 40 layers of MLI) before system weight begins to increase significantly.

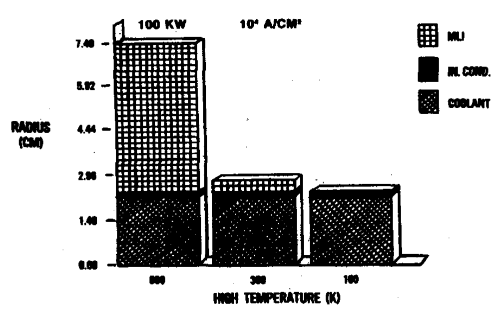

FIGURE 7. SIZE OF BUS ELEMENTS FOR COAX AT 77K

The refrigerator weight can be an important system element at very low temperature. The main advantage of ceramic superconductors for a satellite power transmission bus accrues by increasing the operating temperature from 4 K required for metallic superconductors to greater than 20 K. Less relative advantage occurs by increasing refrigerator temperature to 80 K or above. The optimization of the operating temperature has not been accomplished in this report.

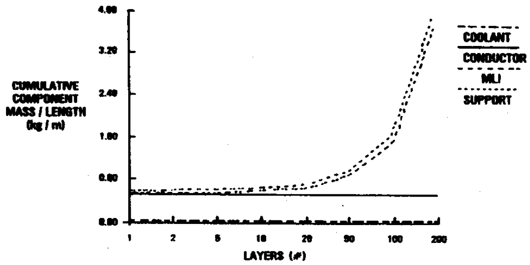

FIGURE 8. CUMULATIVE MASS PER UNIT LENGTH OF A 100. KW, 10^4 A / CM² POWER TRANSMISSION BUS VERSION NUMBER OF LAYERS OF MLI

The refrigerator electrical power requirement on board the satellite can be substantial at 4 K where 2000 electrical watts may be required to remove one watt of heat. A long transmission bus carrying 10's to 100's of kilowatts of electrical power can be shown to require several watts of refrigeration. However, at 20 K and above these refrigerator electrical power requirements will be less than the electrical loss (1.5 to 2%) in a conventional bus. In fact, the refrigerator for the bus will probably be equivalent to the satellite refrigeration mass and power required for sensors and communications.

Discussion/Conclusions

Metallic superconductors requiring refrigeration in the range of 4 K to 10 K are of no benefit to the baseload space power system bus because the refrigeration and insulation constraints are too severe. The new ceramic superconductors that operate in the range of 20 K to 90 K alleviate a great deal of the refrigeration problem and can compete with conventional "hot" bus distribution systems on the basis of mass for a bus exceeding a few meters in length. Figure 4 illustrates the magnitude of potential mass savings if just 1000 A/cm^2 is achievable in the new ceramic superconductors. The mass savings over a "hot" bus is so substantial that the mass of the additional refrigeration required on the satellite can easily be accomodated for temperatures of 20 to 90 K. The thermal loss in the "hot" power bus will also be substantial and will offset the refrigeration cycle electrial power penalty.

The ultimate benefit of the superconducing bus to the space power system will not be the mass savings. The great benefit of the superconducting bus will be the enormous reduction in bus voltage requirements due to the zero voltage drop along the bus. Low bus voltage (less than 100 V_{dc}) will permit a conventional dielectric insulation technology to be utilized as the baseload power of satellites is forced above 10 kW. Successful fabrication of long conductor lengths from ceramic superconductors with current density of 100's A/cm^2 indicate that near term success of a high temperature ceramic superconductor transmission bus on a satellite may be possible.

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