POWER MANAGEMENT AND CONTROL FOR SPACE SYSTEMS

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SUMMARY

Power management and control technology for the large, high-power spacecraft of the 1980's is discussed. System weight optimizations that indicate a need for higher bus voltages are shown. Environmental interactions that are practical limits for the maximum potential on exposed surfaces are shown. A dual-voltage system is proposed that would provide the weight savings of a high-voltage distribution system and take into account the potential environmental interactions. The technology development of new components and circuits is also discussed.

INTRODUCTION

Future use of space for large-scale manufacturing and construction, materials processing, and medical and scientific research will require large quantities of bulk electrical energy. These uses will also impose a series of new diverse requirements on electrical power systems in terms of lower weight, increased life, reduced cost, improved efficiency, and ruggedness. These requirements dictate the development of a high-voltage, utility-type power system and power system control. The technology development proposed is the first phase toward realizing such a power system.

SPACE POWER SYSTEM ELEMENTS

Even though proposed space power systems may vary from a few hundred watts to gigawatts, all will share the same generic system elements:

(1) Power source: Power sources fall into two major classes, solar and nuclear. A technology ready for near-term application in the mid and late 1980's will be the flexible-bodied deployable solar array.

(2) Rotary power transfer: Solar power systems require constant orientation to maintain optimum sun angle. Nuclear systems require thermal control systems pointed toward deep space. In Earth orbital applications, the power source must rotate every 90 minutes. To carry the power across this interface requires a rotary coupling device with low friction, low loss, and long life characteristics.

The simplest, most direct approach is to carry the power across the interface by means of cables. This method requires rapid reverse drive of the solar array to unwrap the cables periodically. Slip rings have been used extensively for power transfer. However, technology adequate for the high powers and high voltages being considered has not yet been developed. The development of on-array conversion systems that create high-frequency alternating current could enable power to be transferred across the interface by noncontact means, by using either inductive or capacitive couplers.

(3) Transmission: As space systems grow in physical size, the design of the power distribution system, in addition to power level, will require serious attention in order to keep line losses to an acceptable level. Distribution and conversion at the load sites will require the development of high power, high-voltage line switches to provide load disconnect capability. Conversion at the load site will require switches, transformers, and other components suitable for operation from the distribution bus.

POWER MANAGEMENT AND CONTROL TECHNOLOGY

Transmission System Characteristics

In the large space systems now under study, power must be distributed from the source over long distances. Thus, careful consideration will first be given to optimizing the distribution system to minimize weight and power losses.

Environmental Interactions

Operation of power systems in the plasma environment of space could present design limitations that must be carefully considered before the system design is finalized.

Power Management Philosophy and Approach

Trade-offs between the optimum distribution system and the limitations imposed by the environment, coupled with the characteristics of the source and the requirements of the load, will factor into the power management philosophy that will be adopted.

Choices will be made between direct- or alternating-current systems, the distribution voltages, the branching philosophy with its attendant switching, and load control. The power management will be controlled with a microprocessor to insure maximum use of the available power, to govern load sharing on a priority basis, and to monitor system performance to prevent catastrophic failures.

The development of a lightweight, efficient multikilowatt power system will require new circuit and component technology. High-power space systems will undoubtedly increase the transmission and distribution voltage levels and require higher voltage switchgear and remote power controllers. To achieve lightweight conversion, it will be necessary to develop new circuit concepts that use higher frequencies. The recent developments of fast high power semiconductors switches and high energy density capacitors provide for significant weight savings.

TRANSMISSION LINE OPTIMIZATION

In an electrical power distribution system, the transmission line contributes to the total system weight in three ways. The first is the weight of the transmission line itself. This is given by

$$W_{TL} = 2dA\ell$$

where

W_{TL} transmission line weight, g

d density of transmission line material, g/cm^3

A cross-sectional area of transmission line, cm^2

ℓ transmission line length, cm

The factor of 2 arises from the need to have a return. If the spacecraft can be used as a return, the weight is only half as much. The analysis in this section does not include the case of spacecraft electrical return.

The second contribution to the weight of the power system, due to the transmission line, is the extra power generation system weight ΔW_{PG} required to make up for power loss in the transmission line:

$$\Delta W_{PG} = \frac{2I^2\rho\ell\alpha_{PG}}{A}$$

where

I transmission line current, A

ρ transmission line resistivity, Ω-cm

α_{PG} marginal specific weight of power generating system, g/W

The third contribution to the weight of the power system, due to the transmission line, is the extra heat rejection system weight ΔW_{HR} needed to handle the heat produced by losses in the transmission line:

$$\Delta W_{HR} = \frac{2I^2\rho\ell\alpha_{HR}}{A}$$

where

α_{HR} marginal specific weight of heat rejection system, g/W

The total weight penalty that can be allotted to the transmission line $\Delta W'_{TL}$ is

$$\Delta W'_{TL} = W_{TL} + \Delta W_{PG} + \Delta W_{HR}$$

$$= 2dA\ell + \frac{2I^2\rho\ell}{A}(\alpha_{PG} + \alpha_{HR})$$

To find the minimum transmission line penalty, set $d\,\Delta W'_{TL}/dA = 0$. This gives an optimum current density of

$$J = \frac{I}{A} = \sqrt{\frac{d}{\rho(\alpha_{PG} + \alpha_{HR})}}$$

and an optimum conductor area of

$$A_{opt} = I\sqrt{\frac{\rho(\alpha_{PG} + \alpha_{HR})}{d}}$$

The weight of the optimum direct-current transmission line in terms of the power transmitted is given as

$$W_{TL,opt} = \frac{2P\ell}{V}\sqrt{\rho d(\alpha_{HR} + \alpha_{PG})}$$

where

P power, kW

ℓ transmission line length, cm

ρ resistivity of transmission line, g/cm^3

α_{HR} specific mass of heat rejection system, kg/kW

α_{PG} specific mass of power generation system, kg/kW

V line voltage, V

When transmission line materials are chosen, the figure of merit used for both minimum transmission line weight and transmission line weight penalty is the product ρd. Figure 1, which compares some of the better known conductors, shows that aluminum is about a factor of 2 better than copper and sodium is nearly another factor of 2 better than aluminum. The optimum direct-current transmission line weight, in terms of power output P and load voltage V is then

$$W_{TL,opt} = \frac{2P\ell}{V} \sqrt{\rho d(\alpha_{PG} + \alpha_{HR})}$$

and the optimum transmission line penalty is twice this.

For a three-phase transmission line, where V is the line-to-neutral rms voltage and the neutral carries no current and can be considered much smaller than the other lines, the total transmission line weight is $3dA\ell$. For this case, the optimum transmission line weight W_{TL} is

$$W_{TL(3\phi,\text{line-to-neutral voltage,no neutral})} = \frac{P\ell}{V} \sqrt{\rho d(\alpha_{PG} + \alpha_{HR})}$$

The total transmission line weight penalty is twice the transmission line weight, as in the direct-current case.

Depending on what is the limiting factor, voltage-to-neutral, line-to-line voltage, rms voltage, or peak voltage may be used in the weight comparison. The effects of these parameters can be given in a factor F_V for the type of voltage distribution, where

$$W_{TL} = \frac{F_V P\ell}{V} \sqrt{\rho d(\alpha_{PG} + \alpha_{HR})}$$

Table I shows the factor F_V for different types of power distribution, with the transmission line weight being minimized for that type of distribution.

The quantity $P\ell/V\sqrt{\rho d(\alpha_{PG} + \alpha_{HR})}$ is plotted in figure 2 for $\rho d = 7.6\times10^{-6}$ for an aluminum transmission line and $\alpha_{PG} + \alpha_{HR} = 30$ kg/kW. Other values of $P\ell$, V, ρ, d, and $\alpha_{PG} + \alpha_{HR}$ may be obtained by appropriate scaling.

Tentative conclusions for minimum transmission line weight penalty are

(1) Use as high a distribution voltage as possible, subject to constraints on insulation converter weights, etc.

(2) Use aluminum (or in an advanced system, sodium) transmission lines rather than copper.

(3) Use three-phase alternating-current, double-voltage alternating-current ($\pm$V), double-voltage direct-current distribution, or a spacecraft return system.

SPACECRAFT-ENVIRONMENTAL INTERACTIONS

Power systems must be very large to generate the multikilowatts needed for future missions, and these systems must operate in the charged-particle environment of space. This requirement introduces the topic of interactions between the large power system and charged-particle space environments.

A pictorial representation of a large space system is shown in figure 3. This illustrates the categories of the interactions of concern. The first category is called "spacecraft passive" - interactions that arise from the environment acting on the spacecraft. The geomagnetic substorm flux of particles occurring at geosynchronous altitude typifies this category of interaction. This flux charges spacecraft surfaces to a value where discharges can occur and cause electronic anomalies. This spacecraft charging interaction has been the subject of intense investigation for the past 3 years.

The second category of interactions, called "spacecraft active," is a new concept and is the principal interaction of concern here. This category is illustrated by the current loop through the environment. The power system will float electrically at some voltage relative to the plasma potential. The exposed interconnects that are positive will collect electrons, and the negative interconnects will collect ions. This collection can be considered to be a current loop through the environment that is parallel to the power system. It is parasitic and represents power losses. This loss depends on plasma density and operating voltages. This interaction must be understood and technology developed to minimize losses.

Other illustrations of this second category of interactions are ion thruster efflux interactions (if these systems use ion thrusters) and electromagnetic interactions. The ion thruster efflux can enhance the plasma density and increase the power system interactions. The electromagnetic interactions are torques introduced by the motion of this large, differentially charged body moving through the Earth's magnetic field.

Solar Array - Environmental Interactions

A ground test investigation of solar array - environmental interactions has been under way at the Lewis Research Center for the past several years. Typical results of testing solar array segments in simulated low-Earth-orbit plasma environments is shown in figure 4. The test is run in the dark with voltages relative to ground applied to the segment by a power supply. The current is measured by a sensor floating in the high-voltage line. For positive voltages up to 200 volts the electron current collection appears to be proportional to the interconnect area, the plasma density and particle temperature, and a reduced value of the operational voltage (about 10 percent). At about 200 volts there is a transition in the current collection from interconnect area to whole panel area collection. At about 500 volts this transition is complete and the electron current collection is proportional to the panel area, the plasma density, and the operational voltage. For negative voltages between 0 and -10 volts there is combined electron and ion current collection. For negative voltages between -10 and about -700 volts the ion current collection seems to be proportional to the interconnect area, the plasma properties, and a reduced value of operational voltages (about 10 percent). At above -700 volts there is a transition to arcing. This arcing is believed to be caused by field emission from the interconnect to the environment. It collapses the operational voltage to essentially zero for the duration of the arc ($\sim\mu$sec).

Spacecraft-Environment Interaction Technology

A spacecraft-environment technology program must be established to understand the interactions, to evaluate the impact on system performance, and to develop design guidelines and recommend practices to minimize the interactions. First, the power losses through the environment must be evaluated as a function of operational voltages. For the large power system, efficiency can be improved and weight reduced if the operational voltage can be increased from the currently proposed 200 volts to a few kilovolts. However, increasing the voltage also increases the environmental losses. Hence, it would be beneficial if, at higher operational voltages, losses could be reduced to a tolerable level.

Ground testing of small solar array segments operating at elevated voltages in simulated space plasma conditions has indicated that arcing can occur on negative voltage areas of the array. At plasma conditions corresponding to about 900 kilometers altitude, this arcing occurs at about -800 volts. Space flight testing has verified this phenomenon. This arcing tendency must be eliminated in any future high-voltage space power system.

The effect of charge deposition on (or in) the materials used on these large space power systems must be understood if the proposed 20- to 30-year operational life is to be realized. This deposition can result in material degradation over long mission life. A charged vehicle can enhance contamination by electrostatically attracting charged particles back to the surfaces and thus reducing transparency of the solar cell covers. The charged-particle environment can be enhanced by ionizing outgassing molecules or by products from arcing.

Both the operational hazards from parasitic currents and arcing and the long-term effects of system degradation must be understood and controlled.

Dual-Voltage System

A high-power system configuration that would provide the weight savings of the optimized distribution system and take into account the potential environmental interactions is a dual-voltage system. The solar array would generate power at 200 to 300 volts that would be upconverted to voltages of about 1000 volts or greater directly on the solar array. The advantages of the upconversion would be lower weight of the rotary power transfer device and lower I^2R losses. The upconverter would be lightweight, efficient, and not regulated. Such a converter could easily be implemented as a voltage multiplier for direct-current distribution or as a series-resonant inverter for alternating-current distribution with a rotating transformer. As the capacity of future power systems increases, system optimizations will probably demand that solar array voltages increase significantly beyond 200 volts. Solutions to the environmental interaction problem will make possible this higher power transmission and distribution.

The high-voltage distribution system would provide power to the user site and be downconverted to the individual load requirements.

HIGH-POWER-CONVERSION TECHNOLOGY

A major portion of any space power system will be the inversion and conversion equipment. To meet the proposed space power system weight goals, it will be necessary to reduce the specific weight of high-power-conversion equipment to less than 1, and probably less than 1/2, kilogram per kilowatt. To achieve these goals, the circuit and component technology has been directed toward higher frequencies. Higher frequency circuits allow a significant reduction in component weight and especially in the magnetics, which usually account for approximately 50 percent of the power conversion weight. Efficiencies must be maintained high so the component weight reduction will not be significantly offset by an increased thermal control mass.

Three basic types of converters and inverters are presently under research and technology development at Lewis: the capacitance diode voltage multiplier (CDVM), the series-resonant inverter (SRI), and the conventional converter. A CDVM transfers energy from its source to the load by capacitance rather than by magnetic coupling and consequently does not require the weight-intensive power transformer. The CDVM uses a higher switching frequency, which reduces the circuit capacitance and the filter inductance. By eliminating the transformer, using a high switching frequency, and incorporating high-energy-density capacitors, the mass and dissipative losses of the CDVM are significantly reduced over present-day power processors. The efficiency of this type of converter has been demonstrated to be typically 95 percent.

The series-resonant inverter using thyristor switches has been developed to a technology readiness status and was chosen as the baseline 3-kilowatt power processor unit for the 30-centimeter mercury ion thruster system. An inhouse study has shown that the SRI technology could be extended to meet the potential requirements of magnetically isolated inverters and converters used in large space power systems. The new series-resonant inverter would be a modular unit whose power output would be determined by the transmission and distribution system selected but that could provide outputs of 20 to 25 kilowatts. The unit would use bipolar transistors presently under development and would switch at frequencies greater than 30 kilohertz. The technology of heat-pipe-cooled magnetics presently under development at the 3-kilowatt level would also be used.

Since frequency plays such an important role in establishing the minimum size and weight of electrical equipment, a technology development effort has been started on a conventional converter with switching frequencies of about 100 kilohertz.

POWER COMPONENT TECHNOLOGY

To reach the performance levels required for power distribution and control in space - in terms of weight, efficiency, life, and reliability - considerable component technology development is required. Some of the more crucial areas for development are described here.

Rotary Transfer Devices

Different parts of a spacecraft often have different orientation requirements. An example is a solar-array-powered spacecraft, where the solar array must face the Sun and the antennas for communications and control must face the Earth. This multiple orientation requirement means that a rotary joint or joints are required in the spacecraft. These joints are available for low power but need development in the high-power ($\geq$100 kW) range. Lewis has a current program to do this.

Fast Switches, Magnetics, and Capacitors

In a high-performance space power distribution system, voltage conversion - such as from a low- or medium-voltage solar array to a high-voltage communications tube - is often required. In the past, voltage conversion equipment has been heavy, with a higher than desired power loss. Lighter weight magnetic devices and capacitors as well as switches to operate at higher frequencies are needed to make lighter weight, higher efficiency converters and ultimately to achieve lower power costs in space. Component development is being done at Lewis on transformers, low- and high-voltage capacitors, diodes, power transistors, and silicon-controlled rectifiers.

Materials

The dielectric materials needed are of the bulk insulation type and the conformal coating, or potting, type. One of the most useful is parylene, which is coated and polymerized from a gas and has exceptional penetrating power. Parylene is extremely inert and free from pinholes. It is being investigated at Lewis for a wide variety of applications.

High-Power, Efficient Switchgear

A missing element for higher power electric distribution in space is the necessary switchgear. Much work has been done at 28 volts, and some at 120 volts. More work is needed for the higher voltage distribution systems (300 V, 1000 V, and up) that will be needed to handle the higher powers for future space applications. Lewis is presently investigating 120-volt dc, 300-volt dc, and 1000-volt dc solid-state switchgear.

CONCLUDING REMARKS

Future use of space for large-scale manufacturing and construction, materials processing, and medical and scientific research will require large quantities of electrical energy. With the growth to multikilowatt power levels, new approaches must be developed to handle the transmission, distribution, conversion, and control of such high power in space.

Preliminary system optimizations strongly favor the high-voltage utility-type power management and control system. A system weight optimization of the transmission and distribution system was performed at three normalized power levels. The results clearly indicate the substantial benefits that can be achieved with high-voltage distribution.

An important consideration in the high-voltage power system optimization will be the limitations imposed by environmental interactions. Higher voltage reduces I^2R losses but increases environmental losses.

One possible high-power system that would provide optimum transmission and distribution and whose design would take into account the potential environmental interactions is a dual-voltage configuration. Such a system would generate solar array power at 200 to 300 volts, would be upconverted to 1000 volts for transmission across the rotary device, and would be distributed to the user at high voltage. Downconversion would be provided to the individual load requirements. This approach is compatible for the near term only; higher power systems will require that the technology of handling high voltage in this environment be understood.

The development of a high-voltage, lightweight, efficient multikilowatt power system will require new circuit and component technologies to reach the performance levels required. The component technology must be developed for efficient rotary power devices; high-speed, high-power semiconductor switches; high-energy-density magnetics and capacitors; and high-power switchgear. To achieve lightweight conversion, it will be necessary to develop new circuit concepts that use higher frequencies.

TABLE I. - VOLTAGE DISTRIBUTION FACTOR

Type of distribution and method of specifying voltage	Voltage distribution factor, F_V
dc, 2 wire	2.00
dc, 2 wire, ±V, balanced	1.00
dc, 3 wire, ±V, balanced	1.225, ($\sqrt{3/2}$)
Single-phase ac, 2 wire, rms	2.000
Single-phase ac, 2 wire, ±V, rms, balanced	1.000
Single-phase ac, 3 wire, ±V, rms, balanced	1.225, ($\sqrt{3/2}$)
Single-phase ac, 2 wire, pk-pk	2.828, ($2\sqrt{2}$)
Single-phase ac, 3 wire, ±V, pk-pk, balanced	1.732, ($\sqrt{3}$)
Three-phase ac, 3 wire, V_{LTN}, rms, balanced	1.000
Three-phase ac, 4 wire, V_{LTN}, rms, balanced	1.155, ($2/\sqrt{3}$)
Three-phase ac, 3 wire, V_{LTN}, pk-pk, balanced	1.414, ($\sqrt{2}$)
Three-phase ac, 4 wire, V_{LTN}, pk-pk, balanced	1.633, ($4/\sqrt{6}$)
Three-phase ac, 3 wire, V_{LTL}, rms, balanced	1.732, ($\sqrt{3}$)
Three-phase ac, 4 wire, V_{LTL}, rms, balanced	2.000
Three-phase ac, 3 wire, V_{LTL}, pk-pk, balanced	2.449, ($\sqrt{6}$)
Three-phase ac, 4 wire, V_{LTL}, pk-pk, balanced	2.828, ($2\sqrt{2}$)

TRANSMISSION LINE MATERIALS

MATERIAL	DENSITY g/cm^3	RESISTIVITY Ωcm	ρd
COPPER	8.96	1.72×10^{-6}	15.5×10^{-6}
SILVER	10.50	1.59×10^{-6}	16.70×10^{-6}
GOLD	19.32	2.44×10^{-6}	47.1×10^{-6}
ALUMINUM	2.6989	2.82×10^{-6}	7.62×10^{-6}
SODIUM	0.97	4.3×10^{-6}	4.17×10^{-6}
BERYLLIUM	1.85	4.0×10^{-6}	7.4×10^{-6}

Figure 1.

RANSMISSION AND DISTRIBUTION SYSTEM MASS VERSUS VOLTAGE

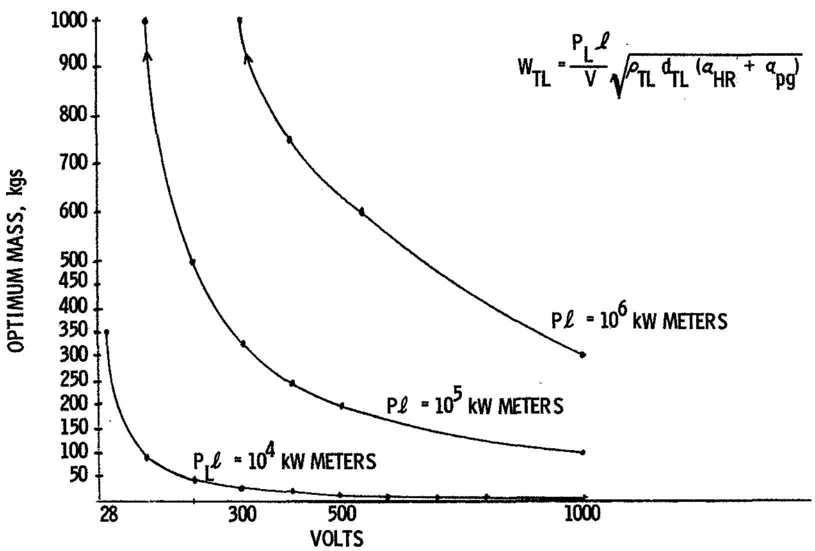

Figure 2.

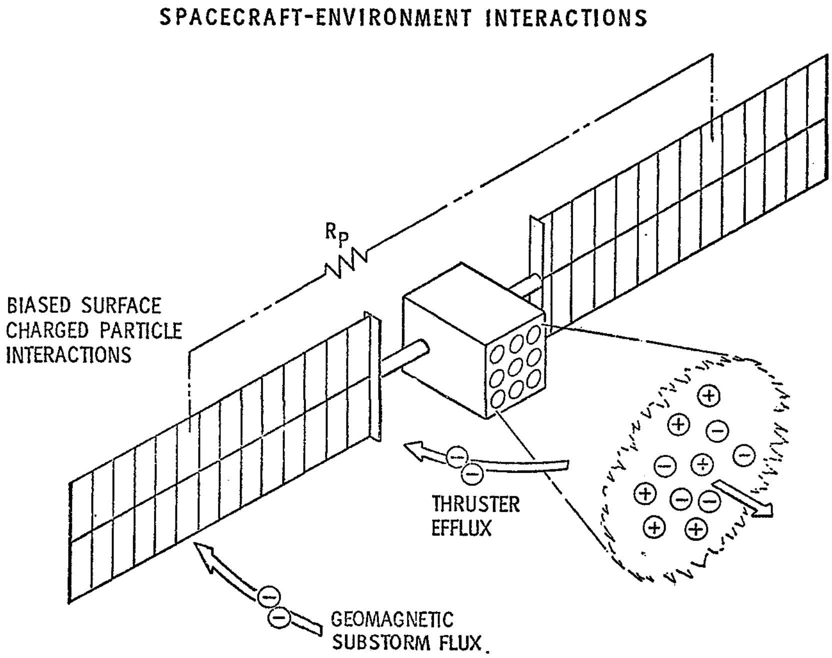

Figure 3.

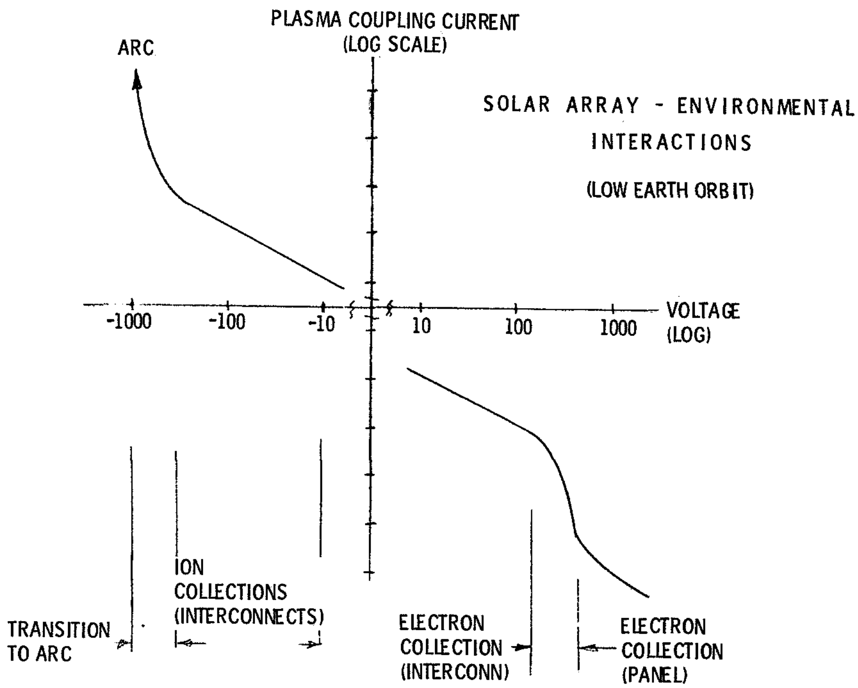

Figure 4.