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A STUDY OF SOME FEATURES OF AC AND DC ELECTRIC POWER SYSTEMS FOR A SPACE STATION

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ABSTRACT

This study analyzes certain selected topics in rival DC and high frequency AC electric power systems for a Space Station. The topics are chosen either because they are potential problem areas or because there seems to be the need for further study and development work.

The interaction between the Space Station and the plasma environment is analyzed, leading to a limit on the voltage of the solar array and a potential problem with [illegible] coupling at high frequencies. Certain problems are pointed out in the concept of a rotary transformer, and further development work is indicated in connection with DC circuit switching, special design of a transmission conductor for the AC system, and electric motors. The question of electric shock hazards, particularly at high frequency, is also explored, and a problem with reduced skin resistance and therefore increased hazard with high frequency AC is pointed out.

The study concludes with a comparison of the main advantages and disadvantages of the two rival systems, and it is suggested that the choice between the two should be made after further studies and development work are completed.

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INTRODUCTION

The design of the electric power system for a Space Station in low earth orbit has received considerable attention over many years. A number of studies[1-6] have been carried out based upon different alternative systems, some primarily DC, some primarily AC, and some a hybrid of the two, but it was clear from the start that the old 28 volt DC system used in previous space missions would no longer be adequate for the Space Station powers envisaged, while the familiar 60 Hz and 400 Hz AC systems would lead to excessive weight of electromagnetic equipment.

The choice of system therefore essentially rests between a relatively high voltage DC and a relatively high voltage, high frequency AC, with some variations based upon these two. The voltages are referred to as relatively high since there are factors that tend to limit these voltages to a few hundred volts, as will be shown below. Too low a voltage, however, would lead to excessive transmission conductor size and losses. The optimum voltage level, as well as optimum frequency if AC, will have to be determined subject to some constraints, in view of the effect that these factors have on the overall station weight and cost.

A study of the two rival systems shows that they are both essentially feasible, subject to some constraints and problems which are discussed below. There are strengths and weaknesses in both systems, and a good case can be made for one or the other. No attempt will be made to choose between the two systems. However, certain specific topics are selected for study, either because they seem to be potential problem areas in one system or the other, or because there may be inadequate data or insufficient past development work.

THEORY AND RESULTS

Plasma Interactions

The voltage of the solar array is limited by the level of discharge from the array to the surrounding plasma and the resulting power loss[7,8]. This discharge is a function of the plasma density, which depends upon the altitude of the Space Station. The optimum station altitude, taking into account correction for aerodynamic drag and the launching of resupply missions from earth, is in the region of 400 km (215 NMi). Unfortunately, this is an altitude at which plasma density is close to a peak[8], Figure 1. At 400 km, the plasma density is of the order of $1 \times 10^6/cm^3$, and the voltage breakdown threshold, Figure 2, is roughly 400 volts. The positive/negative solar array potentials are not symmetrical with respect to the surrounding plasma because of the ease of collection of electrons, resulting in approximately +20V/-380V potential distribution for a 400-volt array. Other factors to be considered are: the additional ionized material introduced through the action of the ion thrusters, the sharp rise in array voltage as the array emerges at the end of the eclipse period into sunlight, and the apparent ineffectiveness of attempting to insulate exposed areas of the array in order to operate at higher voltages. Pending additional plasma data in low earth orbit, it would be prudent to limit the solar array voltage to between 250V and 275V or below.

There is a possibility of resonance between the AC transmission system frequency, if an AC system is used, and some natural plasma frequencies[9], particularly the ion plasma frequency ω_i and the lower hybrid frequency ω_{LH}. These are given by:

$$\omega_i = Q\left(\frac{N_i}{M_i\ \varepsilon_o}\right)^{\frac{1}{2}} \qquad \omega_{LH} = \left(\frac{QeB^2}{M_e M_i}\right)^{\frac{1}{2}}$$

where Q is ion charge, M_i ion mass, N_i ion density, e electron charge, M_e electron mass and B the earth's magnetic field. Estimates of ω_i and ω_{LH} have been made by General Dynamics[3] for a range of altitudes around low earth orbit, giving ω_i as varying from 23 to 74 kHz at 300 km, and from 7 to 43 kHz at 600 km, and ω_{LH} varying from 5 to 10 kHz over the range 300 to 600 km. If resonance coupling were to take place unchecked, large power losses would result. This points to the need for avoiding parallel conductors with an AC system and for proper shielding of electromagnetic equipment. Meanwhile, more work should be done to verify the plasma density data presently available and then to recompute the plasma frequencies.

Rotary Transformer

As part of an AC system, a rotary transformer has been proposed to provide power transfer electromagnetically from the solar array side to the rest of the Space Station, thus avoiding the need for sliding contacts. A General Electric[10,11] design uses four 25-kW modules with a ferrite core and a 0.01" airgap, with a frequency of 20 kHz and a flux density of 0.25 T. The airgap leads to questions about leakage inductance, and the compactness of the transformer achieved through the use of high frequency makes heat dissipation more difficult. Unless proper dissipation is achieved, winding failures could occur leading to a total shut down of power to the Space Station, unless redundancy is introduced by using more than one transformer. Because of the need for an electrical link between the solar array and energy storage equipment (fuel cells or batteries), the use of the rotary transformer gives two options: either energy storage is on the station side of the rotary joint which needs additional conversion equipment, or it is on the array side, adding to the mass of the array and preventing a decentralized storage and conversion system.

Circuit Switching

Although AC circuit interruption has always been easier to achieve than DC because of the availability of current zeros, recent developments[12,13,14] with solid state devices are making DC circuit interruption easier than it has been. The following techniques can be used:

(i) GTOs (gate turn-off thyristors) can switch a circuit very rapidly, from 2 to 10 microseconds. Units have been developed and tested up to 65A, 800V, and GTOs with substantially higher ratings are presently available.

(ii) Power MOSFETs have been tested in units up to 100A, 150V. Because of current rating limits, parallel operation of MOSFETs is needed, unlike the GTOs.

(iii) GTO/SCR systems are used with the GTO driving an SCR bridge circuit, either by controlling the on/off function of the SCRs or by diverting current array from the SCRs. This eliminates bulky commutation circuits from the usual SCR system.

Although there is an obvious need for further development work and there are some problems to be resolved, it is expected that MOSFETs will replace SCR systems up to 30 to 40 kW, and GTOs or hybrid GTO systems will take over at higher power levels.

Transmission Line Parameters

With a DC system, designing a transmission line conductor and computing line parameters present no problem. With an AC system at high frequency, several points should be considered. Skin effect is prominent, leading to a thin hollow tube construction. Reactive voltage drop can be very high unless a coaxial conductor design is used. This can be seen in Figure 3 and Figure 4 which are taken from the work of Renz[8] and his associates. The computation of line parameters at high frequency and with unsymmetrical conductor sections needs further study and experimental verification.

Electric Motors

The traditional DC motor with commutator and brushgear cannot be used because of the plasma environment, and the "brushless DC motor" is in fact an AC motor supplied through a DC/AC converter. With a high frequency AC system, frequency conversion will be needed to avoid excessively high motor speeds. The choice is between the 3-phase synchronous samarium cobalt permanent magnet motor and the 3-phase squirrel-cage induction motor. The latter has the advantages of simplicity, ruggedness and greater long-term reliability. The compactness of the high frequency motor results in the need for proper heat dissipation, since core losses rise substantially with frequency. Additional rotor losses arise with non-uniform rotating magnetic fields[15]

Electric Shock Hazards

In view of the widely varying body resistance, current rather than voltage is used as a measure of electric shock hazard. The let-go current, which is the level at which a person just fails to release an electrode, is a danger threshold. With such a current, prolonged contact with the electrode can lead to respiratory difficulties and to skin changes that greatly reduce skin resistance thereby allowing larger currents to flow. With these higher currents, ventricular fibrillation can set in. Table 1[16] gives typical figures for DC, 60 Hz and 10 kHz AC, and the median let-go currents at 60 Hz are seen to be about one-fifth those with DC. That is why 60 Hz AC is sometimes said to be five times as dangerous as DC[17]. Since skin resistance is by far the largest component of the overall body resistance, skin condition greatly affects the severity of shocks. Voltage also affects skin resistance, high voltage causing a sudden drop of resistance.

Table 1 also shows the let-go currents at 10 kHz to be about equal to those with DC. This is confirmed by the work of Daziel[18,19], and is shown in Figure 5, although the curves of Figure 5 go as far as 7 kHz only. But the skin resistance at high frequency may present a problem. The curves of Figure 6 were taken from the work of Stacy[20] and Burns[21], and show dry skin resistance at 10 to 20 kHz to be about one-hundredth that with DC. If this is confirmed by other studies, it would mean that high frequency AC voltages would have to be much lower than DC voltages for the same degree of safety. Other factors that add to the uncertainties[22] are the effect of the varying time element, the wide range of let-go currents for the different percentiles, and the extrapolation, for obvious reasons, of the ventricular fibrillation threshold currents from the results of animal studies to humans.

Comparison of AC and DC Systems

The main advantages of the AC system are:

1. The system is inherently flexible because of ease of voltage transformations.
2. Circuit switching and fault interruption are inherently easier because of current zeros.
3. With a rotary transformer, sliding contact across the rotary joint is eliminated.

The main disadvantages of the AC system are:

1. More development work is needed for the rotary transformer and other components for high frequency operation.
2. More work is needed in the study and design of a suitable transmission line.
3. There is the possibility of resonance coupling with plasma natural frequencies.
4. There is a possibility of high electric shock hazard through reduced skin

resistance.

5. There are potential problems with synchronizing separate AC buses if needed.

6. There is a need to balance single-phase loads on the 3-phase system in order to minimize the neutral current.

The main advantages of the DC system are:

1. The system is basically simpler and therefore potentially more reliable.

2. With the exception of circuit interruption, system design and components are generally at a higher stage of development than with high frequency AC.

3. The DC system is inherently free of potential problems peculiar to all polyphase AC systems, such as reactive voltage drop, load balancing across phases, synchronization.

The main disadvantages of the DC system are:

1. Absence of current zeros makes circuit interruption more difficult.

2. Circuit switching techniues using GTOs or MOSFETs are still in an early stage of development.

3. DC systems are inflexible in matching a suitable voltage to the load.

4. A sliding contact, as in a slip ring, will be needed for the rotary joint, or the roll-ring if that proves to be reliable.

CONCLUSIONS

Some special features of AC and DC system designs have been studied, and certain potential problems have been pointed out, leading to a comparison between the principal strengths and weaknesses of the two systems.

Interaction of the solar array with the surrounding plasma sets an upper limit to the array voltage at between 250 and 275V or below. The use of a 10 to 20 kHz AC system could lead to resonance coupling with plasma frequencies under certain conditions.

Specific problems with the rotary transformer, DC circuit switching, AC transmission line design and electric motors have been pointed out. The possibility of a higher electric shock hazard at high frequency was referred to.

The comparison between the AC and DC systems shows problem areas on both sides, and it would be advisable to defer making a choice between the two until further development work is done and some of those problems are resolved.

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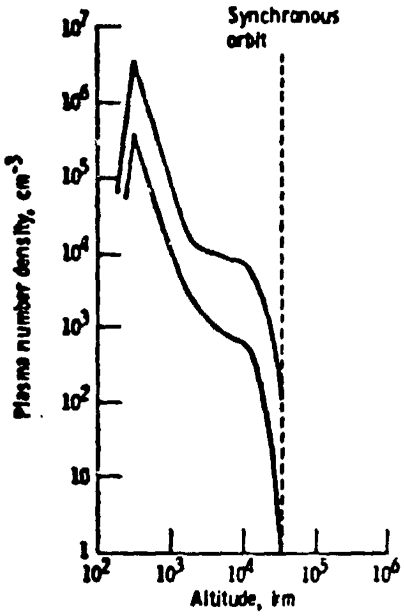


Figure 1. Plasma Number Density as a Function of Altitude in Equatorial Orbit (After Sevens, Reference 8)

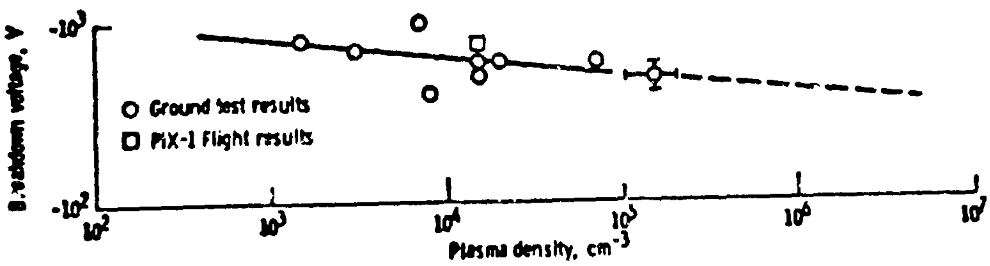
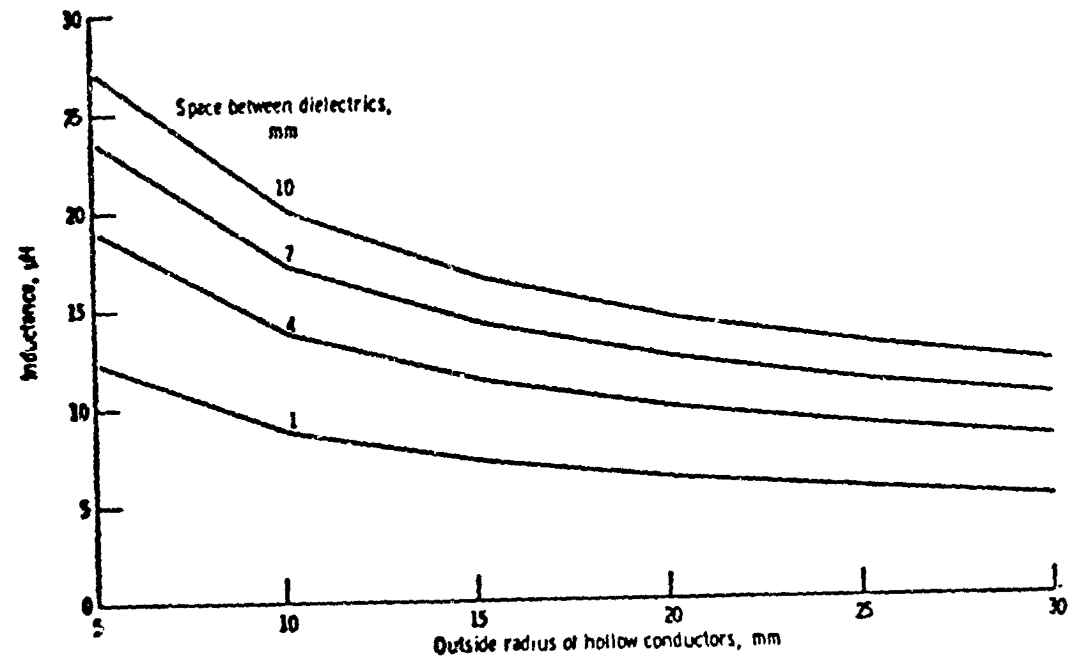
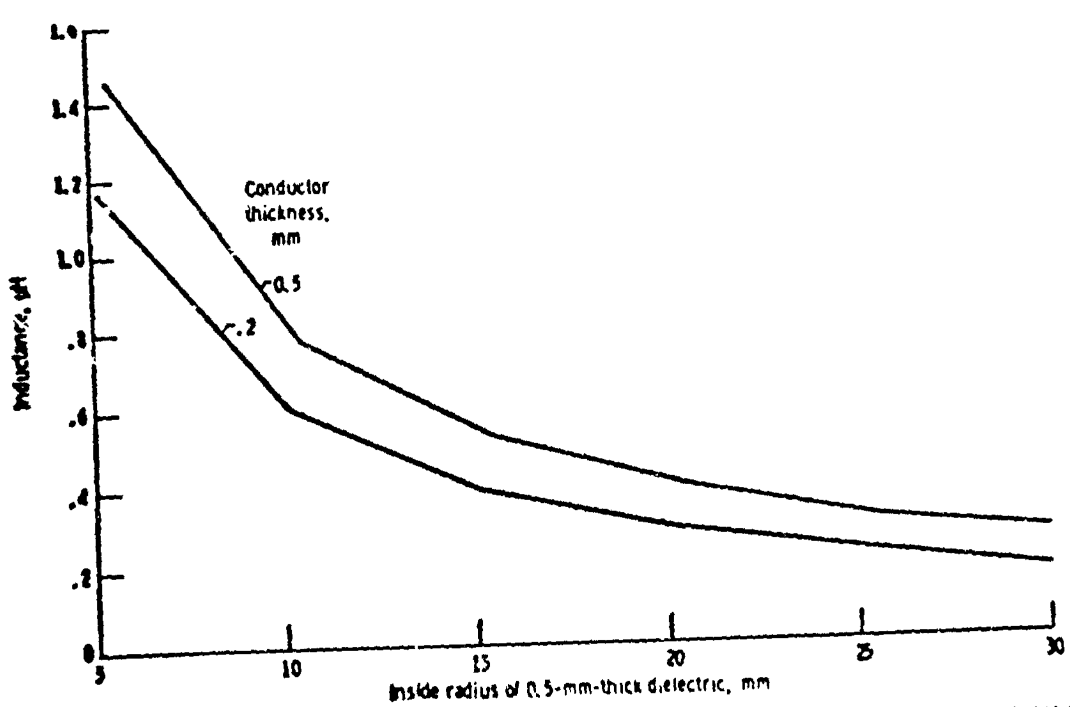


Figure 2. Voltage Threshold for Discharges (After Stevens, Reference 8)



Inductance of 50 m of unshielded parallel conductors as a function of conductor outside radius. Voltage, 1000 V; current, 100 A.

Figure 3. (After Renz, Reference 8)



Inductance as a function of inside radius for 50-m-long coaxial cable. Voltage, 1000 V; current, 100 A.

Figure 4. (After Renz, Reference 8)

Table 1

Quantitative effects of electric current on man.

Effect	Milliamperes					
	Direct Current		Alternating Current			
			60-Hertz		10,000 Hertz	
	Men	Women	Men	Women	Men	Women
Slight sensation on hand	1	0.6	0.4	0.3	7	5
Perception threshold, median	5.2	3.5	1.1	0.7	12	8
Shock – not painful and muscular control not lost	9	6	1.8	1.2	17	11
Painful shock – muscular control lost by ½%	62	41	9	6	55	37
Painful shock – let-go threshold, median	76	51	16	10.5	75	50
Painful and severe shock – breathing difficult, muscular control lost by 99½%	90	60	23	15	94	63
Possible ventricular fibrillation						
Three-second shocks	500	500	675	675		
Short shocks (T in seconds)			$116/\sqrt{T}$	$116/\sqrt{T}$		
Capacitor discharges	50*	50*				

*Energy in watt-seconds

(Taken from Reference 16)

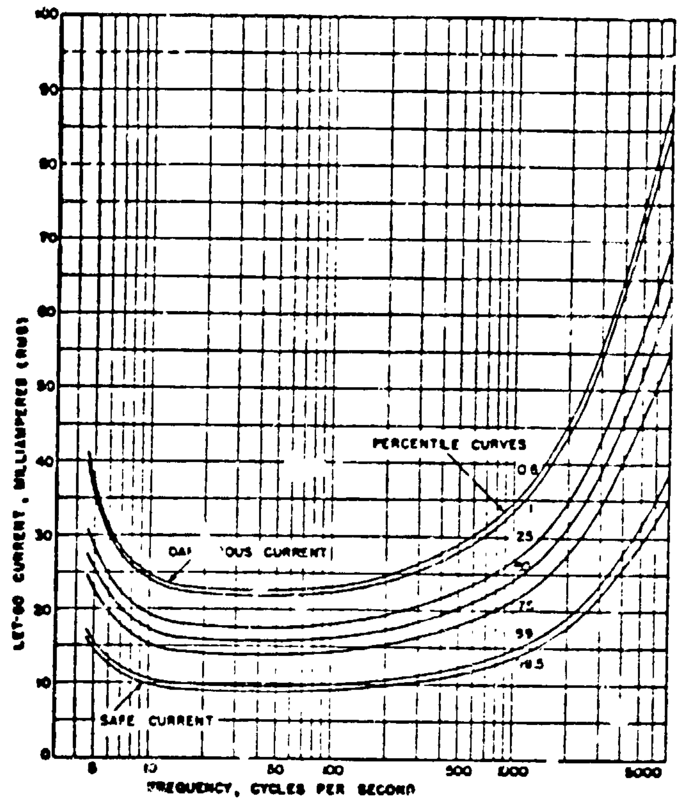


Figure 5. Sine Wave Let-Go Current for Men Versus Frequency (After Dalziel, Reference 18)

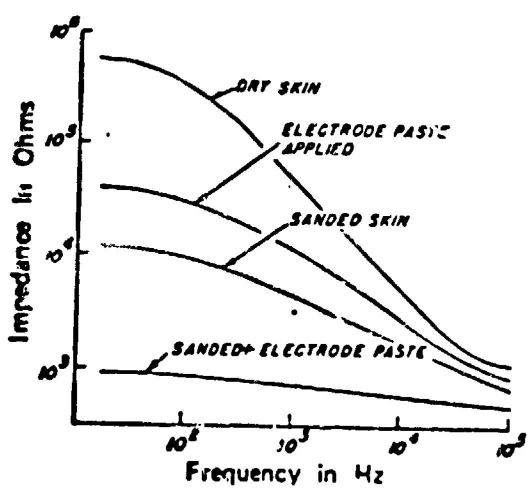


Figure 6. An Example of the Variation of Skin Impedance with Frequency and Condition of Electrode-Skin Contact (After Stacy and Burrs, Reference 17)

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