# Capacitor Bank Charging by Series-Parallel Switching of Solar Arrays

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**The characteristics of capacitor bank charging by series-parallel switching of solar arrays were studied as a power-conditioning technique for magneto plasma dynamic arc jet propulsion systems. This paper presents computer simulation results, tradeoff studies of various methods of capacitor charging, and electronic circuit design considerations.**

## Nomenclature

| | |
|---|---|
| $C_T$ | = total capacitance of the condenser bank |
| $I_0$ | = short-circuit current of each solar array module |
| $I_s$ | = solar array constant current |
| $N$ | = number of solar array sections ($N=2^n$, such as 2, 4, 8, 16 ...) |
| $P_{L1},P_{L2},P_{L3},P_{L4}$ | = first, second, third, and fourth stage losses in switching diodes, respectively |
| $t_1,t_2,t_3$ | = charging time from the starting point to first, second, and third switching, respectively |
| $T_{sp}$ | = total charging time by series-parallel switching |
| $V_c$ | = maximum achievable voltage obtained when all solar array modules are connected in series |
| $V_d$ | = junction voltage drop of parallel connection diodes (CR1 to CR14) |
| $V_s$ | = junction voltage drop of series connection devices (SW-S) |

## Introduction

ELECTRICAL energy from a solar array is stored temporarily in a capacitor bank and discharged in a few milliseconds to attain the several kiloampere arc discharge needed to accelerate the plasma in the magneto plasma dynamics (MPD) arc jet propulsion system.

Constant power charging at maximum available power is essential for efficient use of solar array power. However, when a capacitor bank is charged directly from a photovoltaic array without switching, the charging current is almost constant, and the efficiency of available power use is low. To obtain efficient operation and a low mass system, a power-conditioning unit that increases charging current at low voltage and decreases it gradually according to the increase of charged voltage will be needed to interface the capacitor bank and the solar arrays.

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Instead of using a series of switching-type regulator as a power control unit, series-parallel (S-P) switching of solar arrays has been proposed, in which stages of solar array connections are switched in series and in parallel according to the charged voltage to maintain almost constant charging power.[1,2] This paper presents a brief explanation of the S-P switching concept, the results of the charging-characteristic computer simulations, S-P switching-circuit considerations, and the results of a tradeoff study between this S-P switching and switching-type power converters.

Almost constant power charging also can be performed by S-P switching within the capacitor bank; however, in that case, the switches must handle large discharge currents. Consequently, they would be much heavier than is desirable for solar array switching. Only S-P switching in solar arrays is discussed in this report.

### Series-Parrallel Solar Array Switching

A basic block diagram of the MPD propulsion system, which is a type of electric propulsion system, is shown in Fig. 1. Electrical power is generated in solar arrays and stored in a capacitor bank, with the solar arrays and capacitor bank interfaced through a power control unit. The capacitor bank consists of capacitors and inductors and is a pulse-forming network. The energy stored in the capacitor bank is discharged in a few milliseconds at an electrode with propellant from a tank and regulators. The propellant gas becomes a plasma, which is then accelerated by the large arc-discharge current and is ejected into space. The thrust results from this plasma ejection.

The *I-V* characteristic of a solar cell is shown in Fig. 2. This *I-V* characteristic is typical for a GaAs solar cell,[3] which is one of the options for an electric propulsion power source. Note that although this type of solar cell is used in the analysis, the general design approach and conclusions would be very similar for silicon cell arrays in this application.

The maximum power is only available near the "knee" of the curve (point B). When a capacitor bank charges directly from the solar cell, the charging starts at point A on the curve and moves along the constant current portion of the curve toward point B. The charging power consequently varies almost linearly from zero to the maximum. The average charging power extracted from the cell is approximately half the maximum available power.

The S-P switching concept is as follows. The solar array in an MPD propulsion system is divided into $2^n$ sections (where $n$ is an integer), for example, 8. Each solar array module consists of an array of series- and parallel-connected solar cells. All of the solar array modules are connected in parallel at the start of charging, as shown in configuraion A of Fig. 3. In this case, the *I-V* characteristic is curve a in Fig. 4. The charging proceeds from A to B along curve a.

Where the operating point reaches point B in Fig. 4, the connections of the solar arrays are switched to configuration B in Fig. 3. The *I-V* characteristics become curve b in Fig. 4, and the charging proceeds along this curve. Similar switchings are repeated until the operational point reaches the required voltage (point E in Fig. 4), and the solar arrays are finally in configuration D in Fig. 3, i.e., with all of the solar array modules connected in series. It is clear that, depending on the number of solar array modules and switches, switching the solar array can cause the capacitor-charging operating point to closely approach optimum curve e, which is a constant power curve.

Arranging the solar arrays and switchings in a nonbinary manner may cause the capacitor-charging operating point to approach the optimum curve, e, more closely, but, in this case, some solar array modules are not used in some of the switching stages, and the switching configuration would be quite complicated. Therefore, only the binary switching case is considered in this report.

A simple estimation to determine the number of divisions of a typical solar array that is large enough for effective S-P switching will be shown, based on the assumption that a solar cell provides constant current up to the maximum available power point. The time necessary to charge the condenser bank to maximum achievable voltage, $V_c$, is

$$T_{sp} = \left(\frac{2}{3} + \frac{1}{3N^2}\right)\frac{V_c}{I_s}C_T \tag{1}$$

This equation results from the sum of a geometric series. Each term of the series is the charging time of each solar array configuration, assuming that the solar array provides constant current, $I_s$, up to the maximum achievable voltage, $V_c$.

The time necessary to charge the condenser bank without any S-P switching, e.g., $N=1$, is

$$T_{cc} = \frac{V_c}{I_s}C_T \tag{2}$$

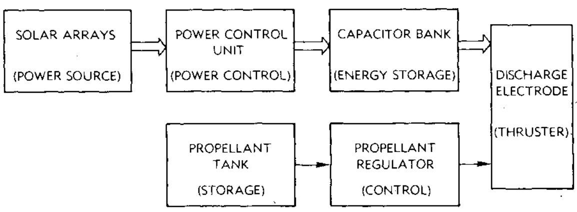


**Fig. 1 MPD arc jet propulsion system block diagram.**

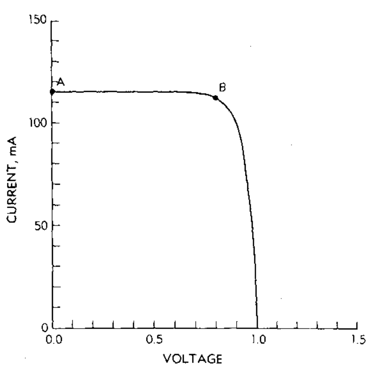


**Fig. 2 Typical *I-V* characteristics of a GaAs solar cell (AMO and 2×2 cm cell).**

It can be observed that the factor $(2/3+1/3N^2)$ represents a reducing factor for charging time. When $N$ becomes very large, this factor obviously approaches 2/3. In the case of $N=8$, the coefficient of Eq. (1) is 0.671875, and the difference from the optimum value, 2/3, is less than 1%. This means that eight sections are sufficient for an effective S-P switching system.

## Computer Simulation

A computer simulation was performed based on using 11,200 GaAs solar cells, with *I-V* characteristics as shown in Fig. 2 and arranged to charge a 10-mF capacitor bank to 500 V. The solar array was divided into eight solar array modules, each consisting of 1400 cells (70 in series, 20 in parallel). The complete configuration of the S-P switching circuit that was analyzed is shown in Fig. 5. Table 1 shows the switch closures needed to obtain the desired circuit configurations. *I-V* curves a through d correspond to configurations A through D, respectively, in Fig. 3, and are *I-V* curves a through d in Fig. 4. Switching SW1 through SW9 in the proper sequence provide the S-P switching control for eight solar array modules.

### *I-V* Characteristic Solar Cell Data

The *I-V* characteristic used for the computer simulation is that shown in Fig. 2. The *I-V* curve was represented by 39 points and linear interpolation was used to approximate the function between these points. The data points were selected to be denser near the "knee" of the curve to represent the actual solar cell curve more accurately.

### Computer Simulation Criteria

The computer simulation involved calculating the charging time necessary to charge the capacitor from a certain point to

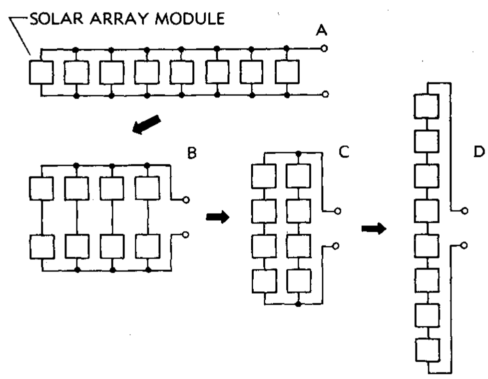


**Fig. 3 S-P switching concept.**

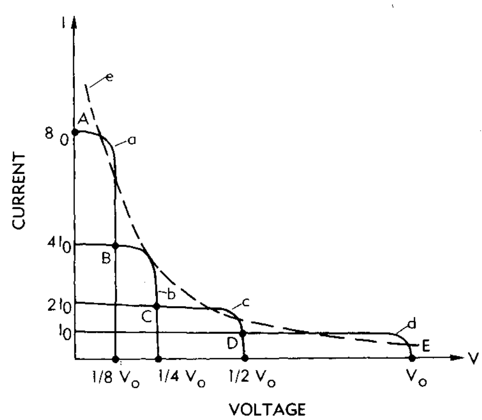


**Fig. 4 *I-V* characteristics of S-P switched solar arrays.**

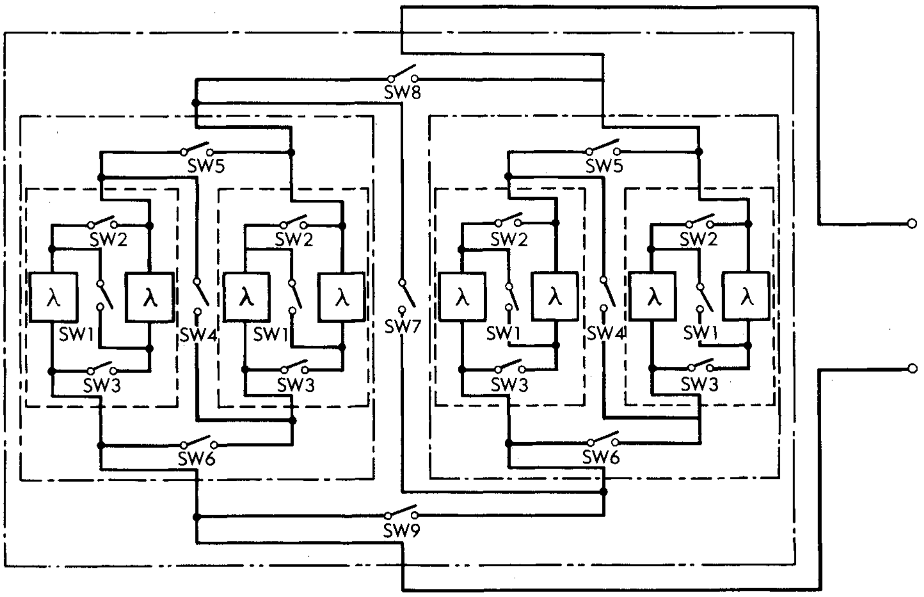


**Fig. 5 Principle of S-P switching circuit.**

**Table 1 Switch status[a] vs configuration**

| Configuration[b] | I-V curve[c] | Switching SW1 | SW2 | SW3 | SW4 | SW5 | SW6 | SW7 | SW8 | SW9 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | a | | × | × | | × | × | | × | × |
| B | b | × | | | | × | × | | × | × |
| C | c | × | | | × | | | | × | × |
| D | d | × | | | × | | | × | | |

[a]The symbol × indicates switch closure. [b]See Fig. 3. [c]See Fig. 4.

**Table 2 Computer simulation parameters**

| | |
|---|---|
| Solar cell type | GaAs (Fig. 2) |
| Number of solar cells in module | 20 in parallel<br>70 in series<br>1400 total in module |
| Number of modules | 8 |
| Charging voltage | 500 V |
| Condenser bank capacity | 10 mF |
| Maximum available power of solar array | 1.033 kW |

**Table 3 Simulation results**

| Item | Series-parallel switching | Constant power charger |
|---|---|---|
| Average charging power, W | 864.3 | 826.1 |
| Efficiency, % | 83.7 | 80 |
| Charging time to first switching ($t_1$), s | 0.03818 | – |
| Charging time to second switching ($t_2$), s | 0.11737 | – |
| Charging time to third switching ($t_3$), s | 0.43574 | – |
| Total charging time to 500 V ($T$), s | 1.44 | 1.54 |

the next point on the solar array *I-V* characteristic curve. The entire *I-V* characteristic of the solar array was divided into a few thousands of intervals, and the numerical integration of the time to go through each interval resulted in the charging characteristics of the condenser bank by the solar array.

In the computer model, S-P switching was performed when the charging time of one solar array configuation was calculated to be longer than that of the next configuration.

### Computer Simulation Result

The parameters used in the computer simulation are given in Table 2. The charging will be performed according to the envelope of the *I-V* curves.

The results are shown in Fig. 6. The irregular curves indicate the results of S-P switching. The regular curves indicate results for an ideal constant power charger with an efficiency of 80%, and thereby serve as a standard.

It is clear that S-P switching nearly follows the constant power charging curve on the average. The charging efficiency of S-P switching is 83.7%, which is comparable to the efficiency of chopper-type regulators. The details of the results and comparison of S-P switching with a constant power charger are shown in Table 3. The losses in switching devices are not included in this result and will be discussed in the next section.

## Practical Implementation of the Switching Circuit

The basic concept of S-P switching is shown in Fig. 7. The term SW-P denotes a parallel connection switch, and SW-S is a series connection switch.

Figure 7 shows a circuit with two solar array modules. Multistage switching, such as the system that was computer simulated, can be constructed by repeating this circuit.

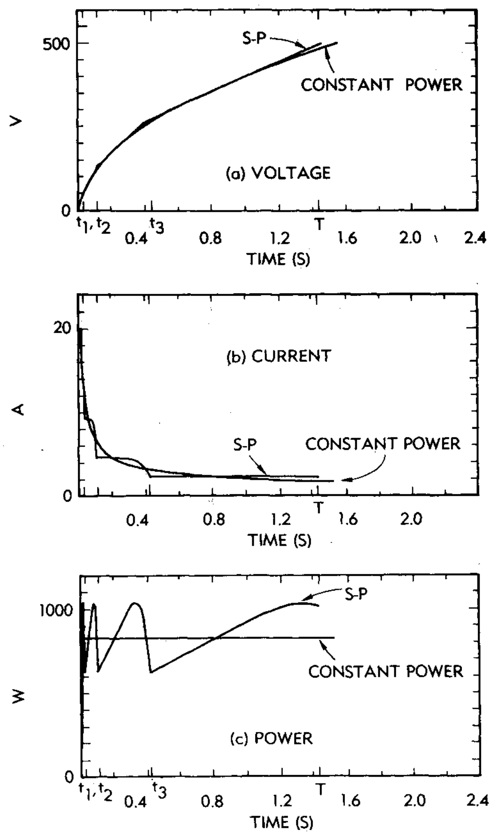


Fig. 6 Computer simulation results for S-P switching.

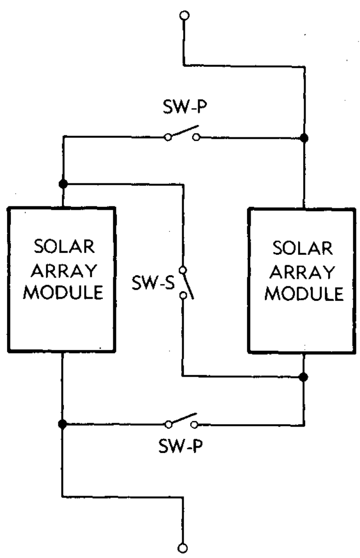


Fig. 7 Basic concept of S-P switching.

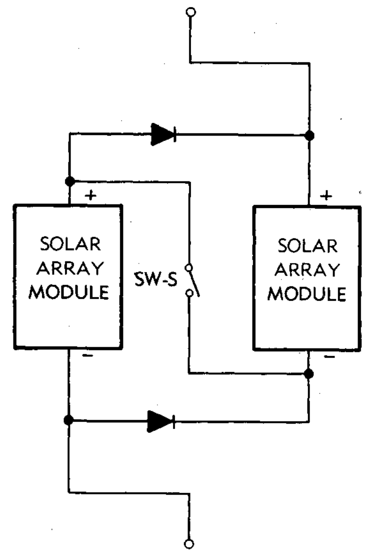


Fig. 8 Simplified circuit for S-P switching.

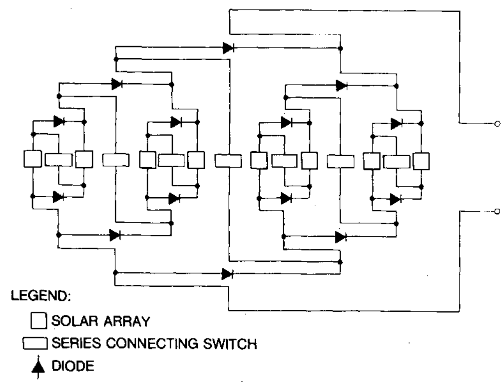


Fig. 9 Schematic diagram of entire solar array switching circuit.

Table 4 Calculated average power loss

| Type of switch | Average losses in switches,[a] W(%) |
|---|---|
| Relay | 3.62 (0.35) |
| SCR | 19.7 (1.9) |
| FET | 35.8 (3.5) |
| Transitor | 19.7 (1.9) |

[a]The maximum power generation in the solar array is 1.033 kW, and the percentage loss is indicated in parentheses.

The circuit can be greatly simplified by replacing two of the three switches in the network by solid-state diodes as shown in Fig. 8. Considerable circuit simplification results in the complete eight-module solar array swithing circuit, as shown in Fig. 9. The switching device, SW-S, can be realized by mechanical switches, silicon-controlled rectifier (SCR) switches, power FETs, or power transistors.

The general formula for estimating the diode and switch losses in the circuit that was computer simulated will now be discussed. Figure 10 shows the schematic connection of diodes and solar arrays from the first to the final stage.

It can be observed by inspection of the schematic that the first-state losses are

$$P_{L1} = (8\times V_d \times I_s) + (4\times V_d \times 2I_s) + (2\times V_d \times 4I_s) = 24V_dI_s \quad (3)$$

assuming that each solar array module provides constant $I_s$ up to switching to the second stage.

The second-stage losses are

$$P_{L2} = 4V_sI_s + 8V_dI_s \quad (4)$$

with similar calculation criteria.

The third-stage losses are

$$P_{L3} = 6V_sI_s + 2V_dI_s \tag{5}$$

and the fourth-stage losses are

$$P_{L4} = 7V_sI_s \tag{6}$$

The average losses are calculated from Eqs. (3-6) and are weighted by the respective charging time of each stage. The average losses are

$$P_{La} = \{t_1P_{L1} + (t_2 - t_1)P_{L2} + (t_3 - t_2)P_{L3} + (T - t_3)P_{L4}\}/T \tag{7}$$

The numerical value of $P_{La}$ is calculated by the actual values of $V_d$ and $V_s$ and the values of $t_1$, $t_2$, $t_3$, and $T$ taken from Table 3. The value of $V_d$ is assumed to be 1 V for simplicity. The current $I_0$ is 2.3 A. The voltage $V_s$ is zero for the relay switch, 1 V for an SCR or transistor, and 2 V for an FET switch. The results of the calculations are listed in Table 4.

Mechanical relay switching has the least losses, but is not acceptable in practical MPD propulsion systems because more than $10^7$ operations (on and off) typically are required.

The SCR switch would not be able to turn off until the engine fired, but this limitation creates no problems. A small transformer-coupled turnoff circuit connected in series with the entire circuit is capable of turning off all of the SCRs by the arc-discharge current from the capacitor bank. A FET switch has more losses than a transistor, but because of the high gate impedance, the driving circuit may be simpler than a transistor. The driving circuit must be isolated from other electronics except when a mechanical relay is used, because all of the solar array voltages must be floating. The mechanical relay is isolated in the device itself.

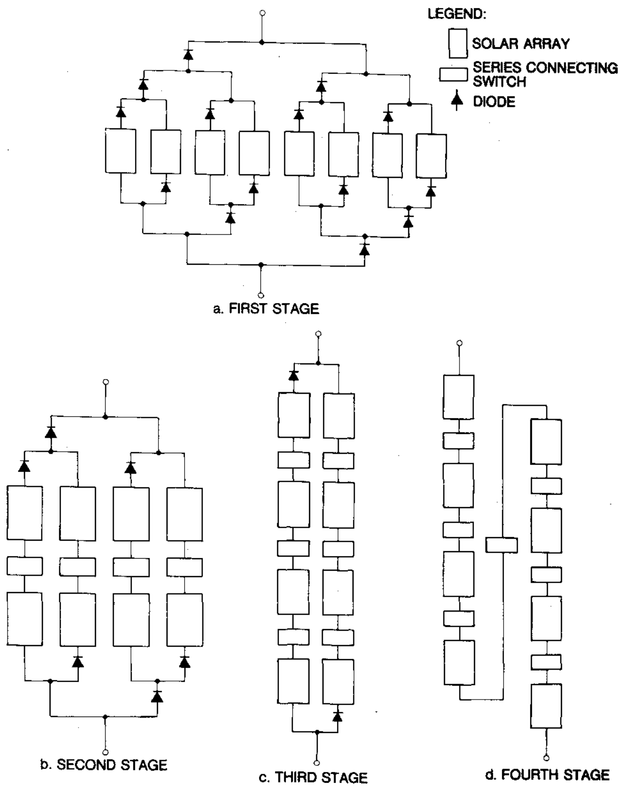


**Fig. 10 Circuit configurations of various stages.**

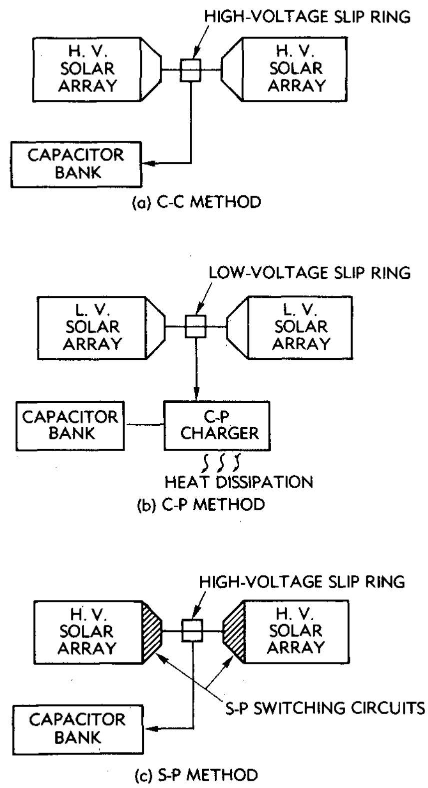


**Fig. 11 Physical schematics of charging methods.**

**Table 5 Comparison of constant-current (C-C), constant-power (C-P), and series-parallel switching (S-P) charging methods[a]**

| Method | Power conditioner parameters: Charging time, s | Mass, kg | Heat dissipation, W | Overall efficiency,[b] % | Overall mass ratio[c] for different solar array mass-to-power ratios, g/W: 30 | 50 | 80 | Solar array voltage |
|---|---|---|---|---|---|---|---|---|
| C-C | 2.4 | ~ 2 | <10 | 53 | 1.5 | 2.6 | 4.12 | 0V to high voltage |
| C-P | 1.54 | ~12[d] | | 80[e] | 1.6 | 2.24 | 3.19 | Constant low voltage |
| S-P | 1.44 | ~3 | 19.7 | 83.7 | 1.0 | 1.61 | 2.51 | 0V to high voltage |

[a]Based on the parameters shown in Table 2 with nonredundant transistors or SCR switches. used. [b]Overall efficiency does not include loss in switches for a simple comparison. [c]Overall mass ratio indicates the ratios of the mass required to produce the same thrust. The 34-kg mass of the S-P using a 30-g/W solar array is taken to be 1. [d] ~10 kg needed in addition for heat dissipation. [e]Assumed value.

There seem to be no switching transient problems except with the first stage turning "on." In this case, the energy stored by the equivalent capacitance of the solar cells will flow at the start of charging. This problem can be eliminated by a small series inductance to limit the in-rush current. This inductance might limit the maximum firing frequency when a repetition rate of 1000 firings/s is considered, but, practically, such a high repetition rate is not planned.

The switching devices should be located on the solar paddle. Consequently, the thermal and radiation environment of these devices would be much more severe than that which normally exists inside the spacecraft structure. The transformer core materials used in the SCR gate trigger circuit could have problems at very high temperatures.

The voltage capabilities of FETs and transistors are almost 500 V maximum, but with SCRs ratings of more than 1kV are easily available.

From the preceding discussion the following conclusions may be obtained:

1) For MPD thruster systems under 200 V in the fully charged mode, a FET or transistor switch design is preferable for reliability.

2) For MPD systems designed for regions over 200 V fully charged, SCRs should be used for voltage endurance.

3) An optically triggered SCR with an optical fiber link is probably optimum in this case. It should be investigated and space qualified.

The S-P method of charging has been discussed already. The solar array potential will increase to a high value, and the higher voltage slip rings are necessary, as with the C-C method. Heat dissipation by the switching devices can be low, as shown in Table 4, and can be distributed in the solar paddle. It is interesting that even if all of the switching devices were to fail closed, the capacitors could be charged by the C-C method as a backup mode.

## Conclusions

In an MPD propulsion system, more than 80% efficiency can be achieved for capacitor bank charging by the S-P method of solar array switching. This value is comparable to the efficiency of a chopper-type dc/dc converter. Furthermore, most of the weight of the charger is saved, and there is no concentrated heat dissipation. Recharging can be very fast, quite close to optimum. The S-P switching can be performed with conventional, commercially available electronic parts of sufficient quality. The only problem is that the solar array must be designed to operate at a high voltage (200-500 V). Insulation techniques and interactions between the solar arrays and the plasma initiated by MPD thrusters should be studied next.

In conclusion, the use of S-P switching to charge a capacitor bank is simple and effective and can produce great progress in the realization of MPD propulsion systems.

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## References

[1]Kuriki, K., Ijichi, K., and Mikoshiba, K., "MPD Propulsion Power Supply Study," *Proceedings of the 25th Joint Conference on Space Technology,* No. 1A18, Kyoto, Japan, Oct. 1981.

[2]Ijichi, K., et al., "Power Supply Study of MPD Propulsion System," *Proceedings of the Symposium on Space Transportation and Propulsion System,"* Institute of Space and Astronautical Sciences, Dec. 1980, pp. 54-66.

[3]Yoshida, S., et al., "High Efficiency AlGaAs/GaAs Solar Cells With High Resistance to Radiation Damage," *Proceedings of the 15th IEEE Photovoltaic Specialists Conference,* 1981, pp. 239-240.