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Solid-State Switching Matrix for Solar Electric Propulsion

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Preface

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

Contents

Tables

Figure

Abstract

To reconnect an ion thruster from one power conditioner to another, a mechanical switching matrix is presently utilized. The current study compares the mechanical solution to a solid-state solution using thyristors. The comparison of the two systems is based on a discussion and analysis of the following parameters: (1) configuration, (2) thyristor characteristics, (3) losses, (4) heat radiators, (5) total weight, and (6) reliability. Comparative conclusions are in terms of weight, size, reliability, and efficiency of the two systems. The study also includes an Appendix outlining the tradeoffs relating to choice of thyristors, as a further effort of system optimization.

Solid-State Switching Matrix for Solar Electric Propulsion

I. Introduction

To reconnect an ion thruster from one power conditioner (PC) to another, a mechanical switching matrix is presently utilized. Two stepping switches are required per one PC; six outputs, that can divert the electrical energy from the above PC to any one of the five ion thrusters or one dummy load, are provided.

The weight of such a mechanical "distributor" is 5.2 lb, with further reduction estimated as possible. The mechanical switches have practically no resistance when closed. When opened, they withstand 4000 V across the open contacts. Encapsulation is supposed to make them immune against contamination and permit an operation in vacuum. In addition to the above power-switching circuit, a logic to drive the above switches is required; the present study, however, excludes the same system.

The present study compares the mechanical solution to a solid-state solution. The comparison of the two systems is to be found in the Conclusion section.

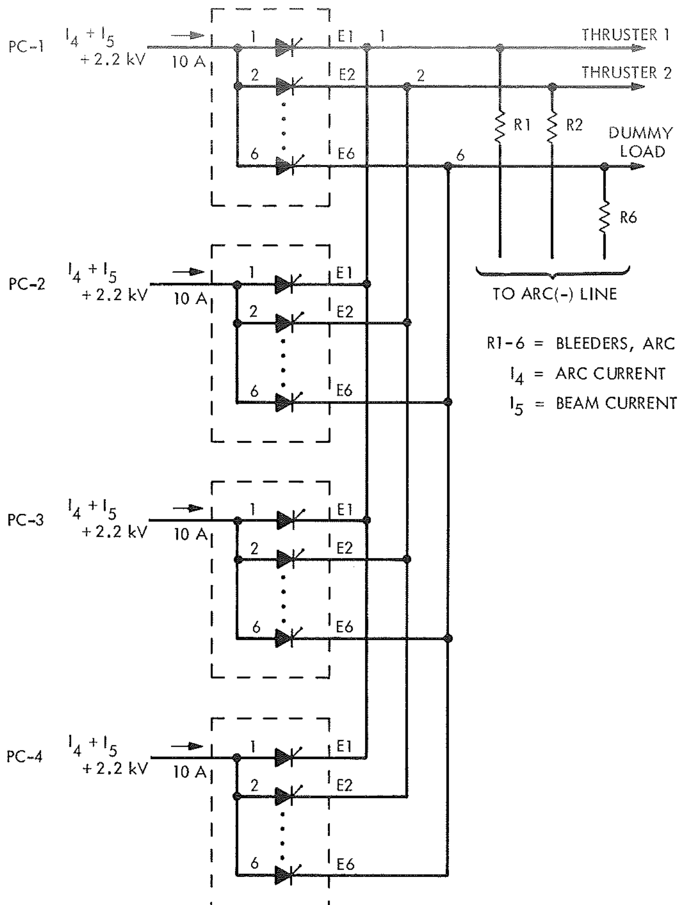
The solid-state switching is performed by means of thyristors that are presently available.

II. Configuration

For the sake of comparison, it is assumed that the system consists of four PCs, five 20-cm ion thrusters, and one dummy load set for checkout. It is further assumed that the electrical energy flows from each of the PCs over 14 lines, as in the case of the mechanical switching.

Figure 1 outlines the principle used to connect one of the supply lines to any of the outputs. Dotted lines indicate the common radiator that rejects the losses generated by the semiconductor. Additional bleeders are shown in the output lines. Not all lines require such a bleeder.

The total number of thyristors required to accomplish the functional requirement amounts to $4 \times 6 \times 32 = 768$ devices. Their weight varies from 0.5 to 12 g. In the case



NOTES:

1. REQUIRED: 4 × 6 = 24 SOLID-STATE SWITCHES.
2. RATED: 12 A, 2.2 kV + MARGIN OF SAFETY.
3. FOR DETAILS, SEE TABLE 1.
4. THE SOLID-STATE SWITCHES, THAT ARE CONNECTED TO THE COMMON INPUT, ARE MOUNTED ON A SINGLE ALUMINUM RADIATOR (SEE TABLE 2) THAT IS CAPABLE OF LIMITING THE SURFACE TEMPERATURE TO A MAX. OF 80°C.
5. THE INPUT POWER IS DIRECTED THROUGH ONE CHANNEL ONLY.
6. BLEEDERS ARE REQUIRED TO LATCH-IN THE THYRISTORS INTO CONDUCTION.

Fig. 1. Solid-state switching matrix for interconnecting four PCs, five thrusters, and one dummy load; detail of arc plus beam power switch

of cascaded devices, slave driving of the cascaded gates is proposed, so that the number of drives can be trimmed down to 4 × 6 × 14 = 336 gates.

III. Thyristor Characteristics

The following characteristics are peculiar to the thyristor:

(1) The thyristor is a P-N-P-N device that can be turned-on by a signal applied to the gate.

(2) As the conduction can only be unidirectional, no alternating current (ac) can be transferred.

(3) The present-day technology imposes a definite limit upon the maximum voltage capabilities of the devices. Because of such limits, devices must in some cases be cascaded in series; this increases the parts count, complicates the gate control, and reduces the reliability of the package.

(4) In cases where loads are non-ohmic but formed by an arc, bleeder resistors must be added to maintain the holding current flow-through devices that were commanded on, since in the absence of such currents, the thyristors will remain off.

(5) A forward loss is associated with each conducting thyristor; to dispose of the heat generated, radiators are required.

(6) Because of the latch-in characteristic of the thyristor, the interconnection of the PC and the thruster has to be made with the PC turned on; in case of the mechanical system, the switching of sets of PCs and thrusters is performed with the power off.

(7) To open the solid-state switch, the source of the electrical power has to be turned off for a fraction of a millisecond.

(8) It should be kept in mind that thyristors are liable to start conducting when triggered by noise. Noise immunization of gates will add to the overall weight.

IV. Losses

From the data of Tables 1 and 2, it appears that the maximum thyristor losses, generated by the system turned fully on, i.e., with all the four PCs delivering full power, will amount to 4 × 143.9 = 575.6 W.

If the power delivered by one PC is assumed to be 2600 W, the overall efficiency will suffer and be reduced by:

$$\frac{575.6}{4 \times 2600}\, 100 = 5.5\%$$

It should be noted that the specified loss may be on the high side, and possibly the 5.5% figure is a pessimistic one.

Table 1. Thyristor requirements for *one* PC plus one thruster (20 cm)

No.	Supply line	Approx. voltage from ground, V	Current, dc max.,[a] A	Thyristor switch: Type[b]	No. in series	PIV*, each, V	PIV*, total, V	Current at 80° C, A	Wt. each, g	Total wt., g	Total forward drop, V	Total loss, W	Holding current, mA	Total wt., gate, resistor/diode, g	Bleeder resistor: W	Bleeder resistor: g	Heatsink[f] for 80° C, in.^{2}
1	ARC (+), screen (+)	2200	12	WE201ZK	2	1500	3000	16	12[c]	24	2 × 1.6	39	20	1	5	8	76.0
2	ARC (−)	2000	10	WE201ZK	2	1500	3000	16	12[c]	24	2 × 1.5	30	20	1	5	8	58.5
3	Engine body	2000	7.5	WE201ZK	2	1500	3000	16	12[c]	24	2 × 1.5	23	20	1	—	—	44.8
4	Cathode tip heater (+)	2000	4	UCR80S	4	800	3200	7	1.4	5.6	4 × 1.2	20	20	2	—	—	39.0
5	Cathode vaporizer (+)	2000	1.5	UCR80S	4	800	3200	7	1.4	5.6	4 × 1.0	6	20	2	—	—	11.7
6	Cathode keeper (+)	2000	1	UCR80L	4	800	3200	1.5	0.505	2.02	4 × 0.9	3.6	20	2	2	3	7
7	Magnet (+)	2000	1	UCR80L	4	800	3200	1.5	0.505	2.02	4 × 0.9	3.6	20	2	—	—	7
8	Accelerator (−)	−2000	0.5	UCR80L	4	800	3200	1.5	0.505	2.02	4 × 0.6	1.2	5	2	10[e]	—	2.3
9	Ground return (−)	0	4	2N4443	1	500	500	—	4[d]	4	1	4	20	0.5	—	—	7.8
10	Neutralizer heater (+)	100	4	2N4443	1	500	500	—	4	4	1	4	20	0.5	—	—	7.8
11	Neutralizer heater (−)	100	4	2N4443	1	500	500	—	4	4	1	4	20	0.5	—	—	7.8
12	Neutralizer keeper (−)	100	2	2N4443	1	500	500	—	4	4	1	2	20	0.5	—	—	3.9
13	Neutralizer keeper (+)	100	1	UCR40L	1	400	400	1.5	0.505	0.505	0.9	1	20	0.5	1	1.5	2.0
14	Vaporizer main (+)	20	2.5	2N4443	1	500	500	—	—	—	1	2.5	20	0.5	—	—	5.0
					32					105.8 g (0.23 lb)		143.9 W		16 g (0.035 lb)		20 g (0.045 lb)	

[a]No ac power shall be utilized.
[b]UCR types are standard = S, or axial lead = L types.
[c]Could be reduced to 9 g.
[d]Estimated.
[e]Cannot be used; other method for latching must be devised.
[f]Surface area = $A[\text{in.}^2] = \{\text{total loss [W]}/(T^4 \times 0.04515)\}\ 0.144 \times 10^8$, where $T[R] = 636°\ [R]$ or $80°\ [C]$,
$= 1.95 \times$ total loss [W].
*PIV = peak inverse voltage.

Table 2. Thyristor requirements for four PCs plus five thrusters plus one dummy load

Supply line No.	Unit wt., SCR*, g	Unit loss SCR*, W	Total wt., 24 × unit wt. SCR*, g	Gate hardware, resistor/diode		Bleeder resistor		Aluminum heat radiator		
				Unit wt., g	Total wt., g	Unit wt., g	(6) Outputs, total wt., g	Unit area, in.^{2}	(4) PCs, total area, ft^2	Total wt., lb or g
1	24	39	576	1	24	8	48	76	2.1	
2	24	30	576	1	24	8	48	58.5	1.62	
3	24	23	576	1	24	—	—	44.8	1.25	
4	5.6	20	136	2	48	—	—	39	1.1	
5	5.6	6	136	2	48	—	—	11.7	0.33	
6	2.02	3.6	49	2	48	3	18	7	0.2	
7	2.02	3.6	49	2	48	—	—	7	0.2	
8	2.02	1.2	49	2	48	—	—	2.3	0.07	
9	4	4	100	0.5	12	—	—	7.8	0.22	
10	4	4	100	0.5	12	—	—	7.8	0.22	
11	4	4	100	0.5	12	—	—	7.8	0.22	
12	4	2	100	0.5	12	—	—	3.9	0.11	
13	0.505	1	12	0.5	12	1.5	9	2	0.055	
14	4	2.5	100	0.5	12	—	—	5	0.14	
◄—— (from Table 1) ——►			2659 g	(from Table 1)	388 g		123 g	(from Table 1)	7.835[a]	6 lb or 2700 g,[b] and 3200 g with mounting hardware

[a]Aluminum plate is 0.050 in. thick; assumption is that only one surface radiates.

[b]Vol. [in.^{3}] × sp. wt. [g/in.^{3}] = 56.45[in.^{3}] × 45.86[g/in.^{3}] plus 4% margin.

*SCR = silicon control rectifier, or thyristor.

Notes: 1. Use devices as per Table 1 and multiply total requirements by 6 (outputs).
2. Configuration, as required for No. 1 supply line, is shown in Fig. 1.

The losses in the bleeder loads can be considered as negligible. Table 1 refers to sizes of resistors to be used rather than losses.

V. Heat Radiators

The following facts should be considered in terms of heat radiators:

(1) It is suggested that whole families of thyristors be mounted on one common radiator in the fashion as shown in Fig. 1.

(2) Most of the radiators must float above the spacecraft ground.

(3) The calculation of the size has been based on the assumption that only one side that faces the outside space shall be used for the heat disposal by radiation.

(4) In designing the radiators, it was assumed that the maximum junction temperature of any thyristor should not exceed 110°C and consequently the maximum temperature of the radiator should not rise above 80°C.

(5) Radiators should be of 0.050-in.-thick aluminum, anodized so as to attain 0.9 emissivity.

(6) The estimated weight of the radiators is 2700 g. This does not include the mounting hardware that may add 500 g.

(7) The required area for radiation has been calculated (Table 2) as 7.84 ft^2.

VI. Total Weight

The data derived in Tables 1 and 2 may be summed up as follows:

Thyristors	4×105.8	= 420 g (approx.)
Radiators and mounting hardware		= 3200 g
Gate hardware	4×16	= 64 g
Bleeders	5×20	= 100 g
Hardware, wire, coating, etc.		= 1216 g
		5000 g (or 11 lb)

The weight of the power conditioning equipment (PCE = 4 PCs) and solar array (SA) will be increased due to additional losses of 576 W (see Section IV above) as shown in Table 3.

Table 3. Weight increase in PCE and SA

Unit	Specific wt., lb/kW	Added wt., lb
PCE	10	5.75
SA	35	20
	Total:	25.75

VII. Reliability

No redundancy has been considered. Loading of the thyristors is considered as conservative and sufficiently derated.

A problem area, that cannot easily be tackled, exists in view of the fact that in most of the cases, failure of a thyristor results in a short between the anode and the cathode. The permanent short of such type could prevent utilization of a "healthy" PC-thruster set, or at least immobilize one good PC.

The reliability could be improved by the following:

(1) Reducing maximum temperature of radiators.

(2) Increasing voltage safety margins.

(3) Increasing sizes of the thyristors.

(4) Providing the most sophisticated noise immunization of gates available.

VIII. Conclusion

Comparative data, in terms of the two solutions, are presented as follows:

(1) *Weight*

Mechanical = 4×5.2 = 20.8 lb

Solid state = 11.0 + 25.75 lb = 36.75 lb

Both are based on the presently available hardware.

(2) *Size*

Mechanical = $8 \times (6.3 \text{ in.} \times 3.1 \text{ in.} \times 2.6 \text{ in.}) = 406.2 \text{ in.}^3$

Solid state = $7.84 \text{ ft}^2 \times 2 \text{ in. high} = 2258 \text{ in.}^3$

(3) *Reliability*

This is not compared, but intuitively the mechanical solution seems to be superior.

(4) *Efficiency*

Loss of the overall efficiency is associated with the solid-state solution.

The Appendix outlines the tradeoffs resulting from applying large-size thyristors and points out the possibility of system optimization by means of a parametric study.

The above report does not claim to be a final version of the design. It is generated as a first attempt to establish the feasibility of the concept.

Appendix

Choice of Thyristors

As a follow-up to the calculations presented in Table 1 and Table 2, a further effort of system optimization has been made and is presented below, as follows:

(1) From Table 1, the total losses per "one PC" switch module were listed as 143.9 W.

(2) The total radiator weight required to dissipate such losses (from Table 2) is 3200 g.

(3) This total weight gives a 22.2 g/W scaling factor.

(4) Substituting on lines 1, 2, 3 of Table 1 the WE201ZK type thyristors with the WE250ZK types, total watt losses can be reduced from $39 + 30 + 23 = 92$ W to 59 W, or by 33 W reduction.

(5) The above reduction in power dissipation reduces the weight of the radiator by 732.6 g.

(6) The above reduction in power dissipation additionally reduces the weight of the power conditioning equipment and solar array by: $45 \text{ lb/kW} \times 33 10^{-3} \text{ kW} = 1.485 \text{ lb} = 675$ g.

(7) The WE250ZK thyristors are heavier and their weight goes up from 72 g to $6 \times 140 = 840$ g, or by 768 g increase.

(8) The new thyristors offer a much higher margin in current deratings as they can carry 125 A(rms) instead of 16 A(rms).

(9) The holding current of WE250ZKs is higher so that the bleeder sizes and losses must go up.

The conclusion from the above facts appears to be that a number of parameters will influence the choices of devices to be used. Before an optimum hardware is selected, further parametric studies will be required.

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16. Abstract

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