NASA TECHNICAL MEMORANDUM

NASA TM X-73505

NASA TM X-73505

SERIES-PARALLEL METHOD OF DIRECT SOLAR ARRAY REGULATION

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September 1976

(NASA-TM-X-73505) SERIES-PARALLEL METHOD OF DIRECT SOLAR ARRAY REGULATION (NASA) 16 p HC A02/MF A01 CSCL 10A

N77-10641

Unclas
G3/44 09523

1. Report No.
NASA TM X-73505

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
SERIES-PARALLEL METHOD OF DIRECT
SOLAR ARRAY REGULATION

5. Report Date

6. Performing Organization Code

7. Author(s)
S. T. Gooder

8. Performing Organization Report No.
E-8906

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
A 40 watt experimental solar array was directly regulated by shorting out appropriate combinations of series and parallel segments of a solar array. Seven regulation switches were employed to control the array at various set-point voltages between 25 and 40 volts. Regulation to within ±0.5 volt was obtained over a range of solar array temperatures and illumination levels as an active load was varied from open circuit to maximum available power. A four-fold reduction in regulation switch power dissipation was achieved with series-parallel regulation as compared to the usual series-only switching for direct solar array regulation.

17. Key Words (Suggested by Author(s))
Energy conversion
Solar array

18. Distribution Statement
Unclassified - unlimited
STAR category 44

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

Direct regulation of a solar array to meet load voltage and/or current requirements offers two major system improvements over conventional power processing. These are a significant reduction in power processing weight and complexity and an increase of power system efficiency to 99% or better. The usual method of directly regulating a solar array is to short out series sections of the solar array to electronically eliminate them from the power producing capability of the array. However, as the current capability of the solar array increases, the power dissipated in the shorting switches rises significantly. An alternate regulation scheme, which reduces switch dissipation, is to short out a combination of series and parallel array sections. This paper presents the results of an experimental program in which a 40 watt demonstration solar array was regulated by series-parallel switching at set-point voltages between 25 and 40 volts. Seven regulation switches were used to provide regulation to within ±0.5 volt of the set-point voltage. Regulation was maintained over a range of solar array temperatures and illumination levels as an active load was varied from open circuit to maximum available power. A four-fold reduction in the switch power dissipation was achieved with series-parallel regulation as compared to the usual series-only switching solar array regulation.

INTRODUCTION

Arrays of silicon solar cells are the major source of electrical power for spacecraft. However, the voltage at which a solar array produces power is not constant but rather varies with the current demand of the spacecraft loads, the temperature of the solar cells, the intensity of solar illumination, and the degree of electrical and/or mechanical degradation of the array. Present solar array power management relies on central voltage regulators and/or distributed power processors to provide the various regulated d.c. voltages required aboard a typical spacecraft. These regulators and processors exact significant power system penalties in terms of power loss, weight, system cost, and reliability. Considerable efforts are being made on alternate system concepts to reduce these system penalties.

One of the most promising concepts is the Integrally Regulated Solar Array (IRSA); a well known implementation of this system is the High Voltage Solar Array (HVSA). The IRSA system provides regulated d.c. power from a controlled solar array directly to the using load without an intervening power processor. References 1 to 3 discuss system configurations and reference 4 describes some operational results obtained with a prototype IRSA system. Typically, the solar array is subdivided into a number of series blocks, some of which are paralleled by shorting switches. The switchable blocks are usually sized by voltage in a binary fashion, but this is not a concept requirement. Figure 1 is a block diagram of a typical IRSA system, consisting of the solar array, the regulation switches, control logic, voltage sensor, and a d.c. load. This basic system, in terms of control philosophy and mechanization is independent of the specific regulation voltage required. The only regulator variations necessary in going from a regulated 30 volt solar array to a regulated 30 kV array are in the size of the switchable array blocks and the voltage and current capabilities of the regulation switches.

In any spacecraft power system, one of the major considerations is the amount of power lost in electronic component dissipation which is directly reflected in both the size of the solar array and in the amount of thermal radiating area that must be provided. The IRSA system has three sources of waste heat. When a solar cell operates at short circuit, the cell temperature rises about 2° to 4° C over the temperature of a cell operating at the maximum power point. Since the rise is small and occurs out on the solar array, which is a large radiating area, this effect is of no great concern to the spacecraft designer. The control electronics typically require a few tenths of a watt, which is negligible. The major source of thermal dissipation in the IRSA system is in the shorting switches themselves. The switch typically used (refs. 5 and 6) is basically a saturated transistor with series and parallel diodes for transient protection. When a switch is on, the maximum power dissipated is the switch voltage drop (approximately 1 V) times the array short circuit current, plus the switch drive power. Thus for large regulated solar arrays - either high voltage/high power or low voltage/high current - the switch power dissipation becomes a significant factor in total spacecraft power system thermal design. This report discusses the experimental investigation of a method of directly regulating a solar array which has the potential of significantly reducing the power dissipated in the regulation switches.

SYSTEM CONCEPT DESCRIPTION

The usual IRSA method of directly regulating a solar array employs array voltage control. That is, the effective number of solar cells in series is varied by means of shorting switches to maintain a constant voltage. Figure 2(a) is a sketch of solar array voltage-current (V-I) curves that can be generated by progressively shorting out more and more series solar cells. All that is needed for regulation is control electronics that will select the appropriate V-I curve (short the necessary cells) to maintain a constant voltage regardless of the load current. The resulting V-I curves are shown, in figure 2(b), with and without regulator operation. Similarly, a constant current solar array can be produced by shorting out parallel solar cells (figs. 2(c) and (d)). But since most spacecraft loads are designed for a constant voltage power source, the current-regulated solar array has not been actively pursued.

The alternate method of solar array voltage regulation investigated in this work is a combination of array voltage and array current control. That is, shorting switches are used on both series and parallel blocks of solar cells. This combination requires more shorting switches than the straight voltage control method. However, the current carried per switch and thus the total power dissipated in the switches will be less. In the straight voltage control method, each switch must carry the short circuit current of the full array; in the series-parallel arrangement, each switch carries only the short circuit current of its array segment. Figure 3 is a block diagram of a very simple regulated solar array system with two series and two parallel regulation blocks which are binary weighted in voltage and current, respectively. Note that blocking diodes are included to isolate the parallel blocks when they are shorted out. Figure 4(a) is a sketch of the V-I curves that could be obtained with various switch combinations for this very simple series/parallel regulated array. For example, the four curves of section "A" of the figure are produced by shorting out the two parallel array blocks and then progressively closing the series switches. The remaining curves are produced by progressively opening the parallel switches and again exercising the series switches. Figure 4(b) shows the unregulated and regulated V-I curves that would be produced with this simple four switch series/parallel regulated solar array. As can be seen from the figure, the voltage regulation is rather coarse, but can easily be improved with the addition of more series and/or parallel switchable blocks.

EXPERIMENTAL SET-UP

A series/parallel regulated solar array system was breadboarded using a small portion of the LeRC 1 Kilowatt Laboratory Solar Array Facility which is described in reference 7. The solar array consists of 96 (2 cm × 2 cm) solar cells in series and 8 solar cells in parallel. Under nominal 1 sun illumination, the unregulated open circuit voltage is 52 volts and short circuit current is 1.01 amperes. A ramp-driven power transistor provided a continuously (open to short circuit) variable load on the solar array.

Seven switches are used to regulate the solar array output. They are hybrid circuit versions of the switch described in reference 5. Figure 5 is a schematic of the experimental solar array. Four switches are tapped into one series string for voltage control. These switches short out 4, 8, 16, and 32 solar cells of the string. Three switches are used for current control and short out 1, 2, and 3 parallel strings. The remaining parallel string is unswitched. All the parallel sections are isolated by blocking diodes.

Figure 6 is a schematic of the solar array regulation logic. This same circuit is used for voltage or current only regulation. The solar array voltage is sensed with a divider and compared to an adjustable reference. If the sensed voltage is within an adjustable voltage window, the up-down binary counter is disabled. If the sensed voltage is too high, the counter counts up, turning switches on to short out more array sections until the voltage is within the window. If the voltage is too low, the counter counts down, turning switches off. There are also "end stops" to prevent the counter from continuously cycling when all switches are on and the voltage is still too high or when all switches are off and the voltage is too low.

Regulator operation can best be understood by following the changing switch states as a load is varied from zero current to the maximum available. For simplicity the following is based on the simple four switch regulator in figure 3. This system has two series switches (S1 and S2) and two parallel switches (P1 and P2). The seven switch regulator (fig. 5) used for the experimental solar array functions in the same manner. When the load is drawing zero current, all four switches are on (shorting out the regulation segments of the solar array); the regulator is inhibited by the end stop, and the solar array is at the open circuit voltage of the unswitched section. As load current is drawn, the array voltage begins to decrease. When the voltage falls below the set-point, the regulator is enabled and begins to count down in binary fashion beginning with the least significant bit which is controlled by S1. The count proceeds in binary fashion: S1 off and S2, P1, P2 on; S2 off and S1, P1, P2 on; S1, S2 off and P1, P2 on. The next step of the counter will turn P1 off which adds to the current capability of the array and S1 and S2 are again turned on. The count continues until the maximum current capability of the solar array is reached at which time all the switches are off and the regulator is again inhibited by the end stop. If the load current begins to decrease, the voltage will tend to rise and the counter begins to count up, turning switches on, again in binary order. Using 1 for on and zero for off, the table below shows the various switch states for a four-switch regulator.

	P2	P1	S2	S1	
Zero load current	1	1	1	1	End stop
	1	1	1	0	
	1	1	0	1	
	1	1	0	0	
Add I-capability	1	0	1	1	
	1	0	1	0	
		. . .			
Add I-capability	0	1	1	1	
	0	1	1	0	
		. . .			
	0	0	0	1	
Maximum capability	0	0	0	0	End stop

RESULTS

System characterization and performance were measured on V-I curves with an x-y plotter using the ramp-driven transistor to provide a smoothly varying load from solar array open circuit to short circuit. Figure 7 is a plot of the solar array characteristics for all combinations of switches on and off. Curve A is for all switches on - minimum solar array power capability. Curve B is all switches off - maximum power capability. The nonuniformity of the curves, for example at C and at D, is the result of several factors. The 1 volt switch drop is more significant for the small (4 and 8 cell) switched sections. The solar cell strings are not perfectly matched for V-I characteristics. In addition, there is some nonuniformity in the illumination system used. However, these irregularities do not prevent proper functioning of the regulation system; thus demonstrating the insensitivity of a directly regulated array system to such factors as solar cell mismatch.

Figure 8 is a group of V-I curves taken for various regulation voltage set-points from 25 to 40 volts. The maximum deviation from the regulation point is approximately ±0.5 volt. (The glitch appearing on 3 of the curves at approximately 0.9 A is the result of load ramp circuit noise.) Similar sets of curves were taken while varying the array temperature and illumination as well as the load. In all cases the system maintained regulation.

Regulation system efficiency is very good, as is the case with any direct solar array regulation scheme. For the series/parallel regulator on this nominal 40 watt test array, the maximum power dissipation is approximately 1 watt. If an equivalent four-switch straight voltage-control regulator had been used on this array, maximum power dissipation would have been 4 watts. The reduction in dissipation with the series/parallel regulator becomes even more striking when high power solar array regulation is considered. Further dissipation reduction is possible, if regulation down to open circuit (zero load current) is not required. In this case, some parallel blocks of solar array are not switched. The effect of this on the solar array V-I characteristic is the lump at the left-hand edge of the regulated V-I curves in figure 8.

CONCLUDING REMARKS

Direct regulation of a solar array to meet load voltage and/or current requirements offers two major system improvements over conventional power processing. These are a significant reduction in power processing weight and complexity and an increase of power system efficiency to 99% or better. A direct solar array regulation scheme was experimentally examined on a 40-watt laboratory solar array. Regulation was accomplished by shorting out appropriate combinations of series and parallel solar array segments. Regulation was maintained for an avtive load under a variety of solar array temperature and illumination conditions. Using the series-parallel regulation technique, a four-fold reduction in switch power dissipation was achieved compared to the more usual series-only switching for direct solar array regulation.

Extension of the series-parallel regulation scheme to larger solar arrays is straightforward. Higher voltages require more solar cells in series and an adjustment in the number of cells in the series regulation sections. In addition, more series blocks may be needed to provide tighter regulation and/or a wide range of set-point voltages. The first series switch (least significant bit for the counter) controls the smallest series segment, followed by the remaining series segments. Binary weighting requires the fewest switches, but the regulator will function properly as long as each successive bit is as large or larger than the preceding (lower bit) sections. The parallel segment switches follow the series segments in the same order - lowest current section first. Thus this regulator can control very large solar arrays with the simple addition of more regulation switches and additional counter range.

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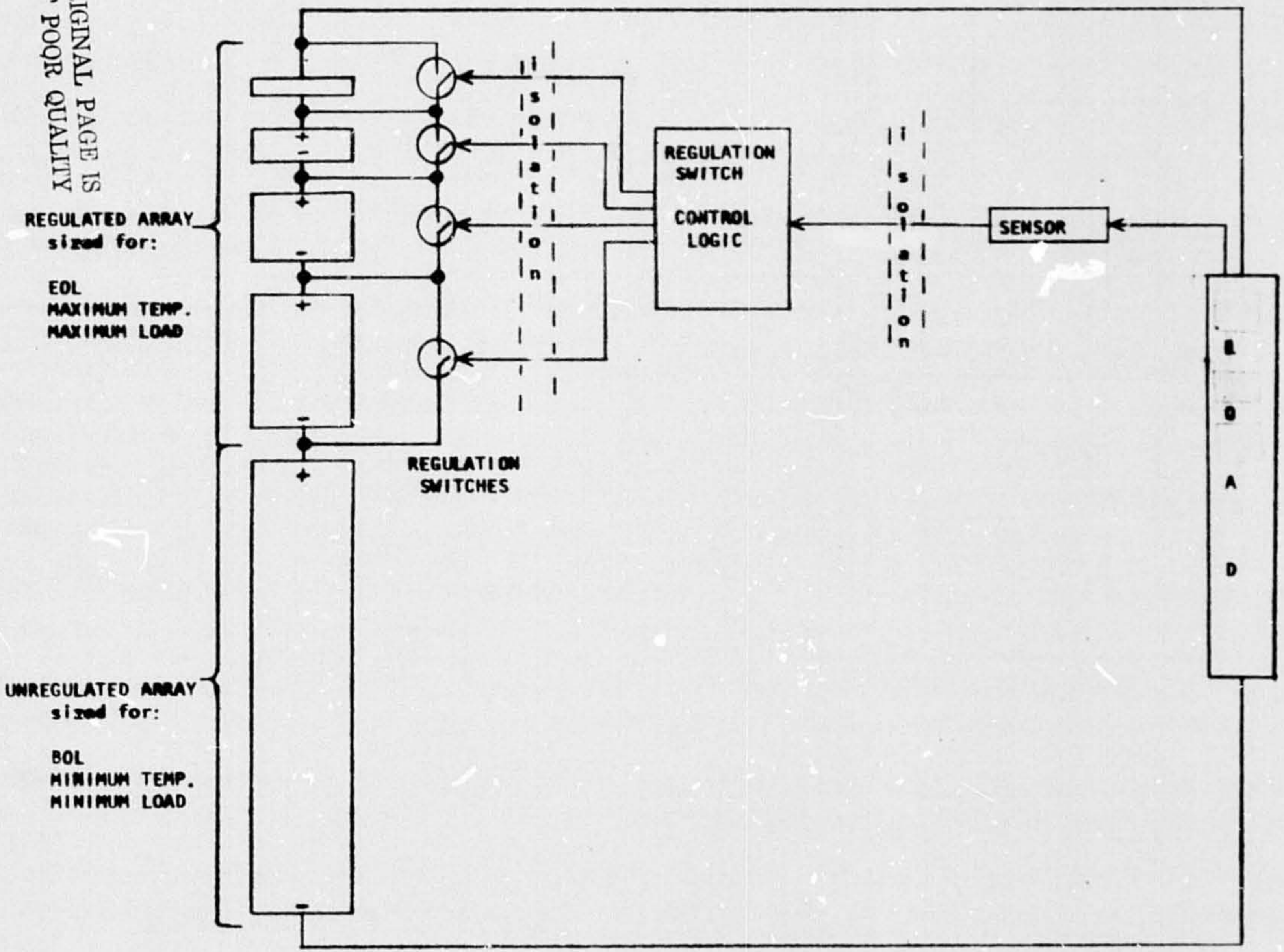


FIGURE 1. BLOCK DIAGRAM OF A TYPICAL REGULATED SOLAR ARRAY

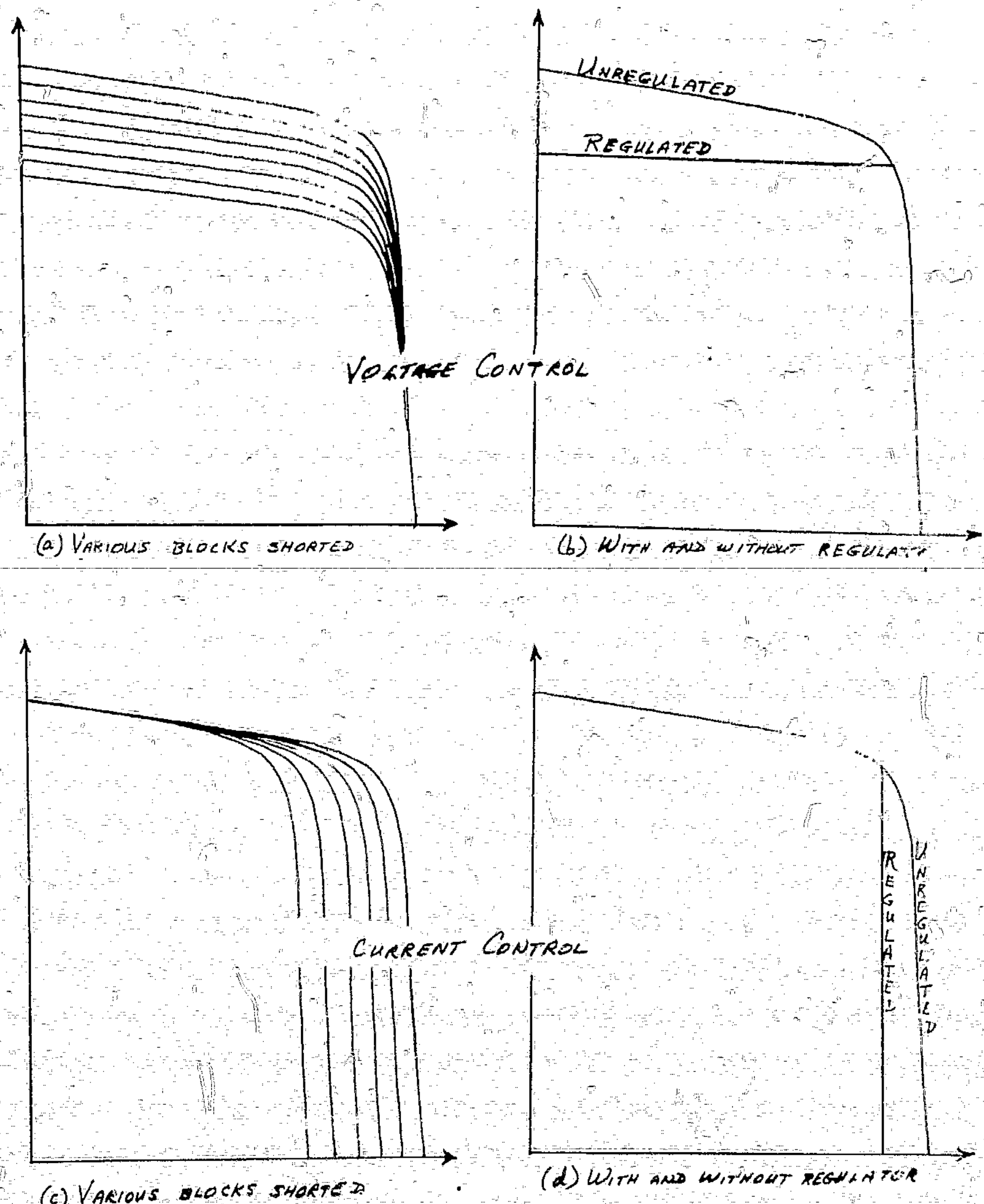


FIGURE 2. REPRESENTATIVE SOLAR ARRAY CURVES FOR VARIOUS SWITCH COMBINATIONS ON SIMPLE VOLTAGE (a & b) AND CURRENT (c & d) REGULATED ARRAYS

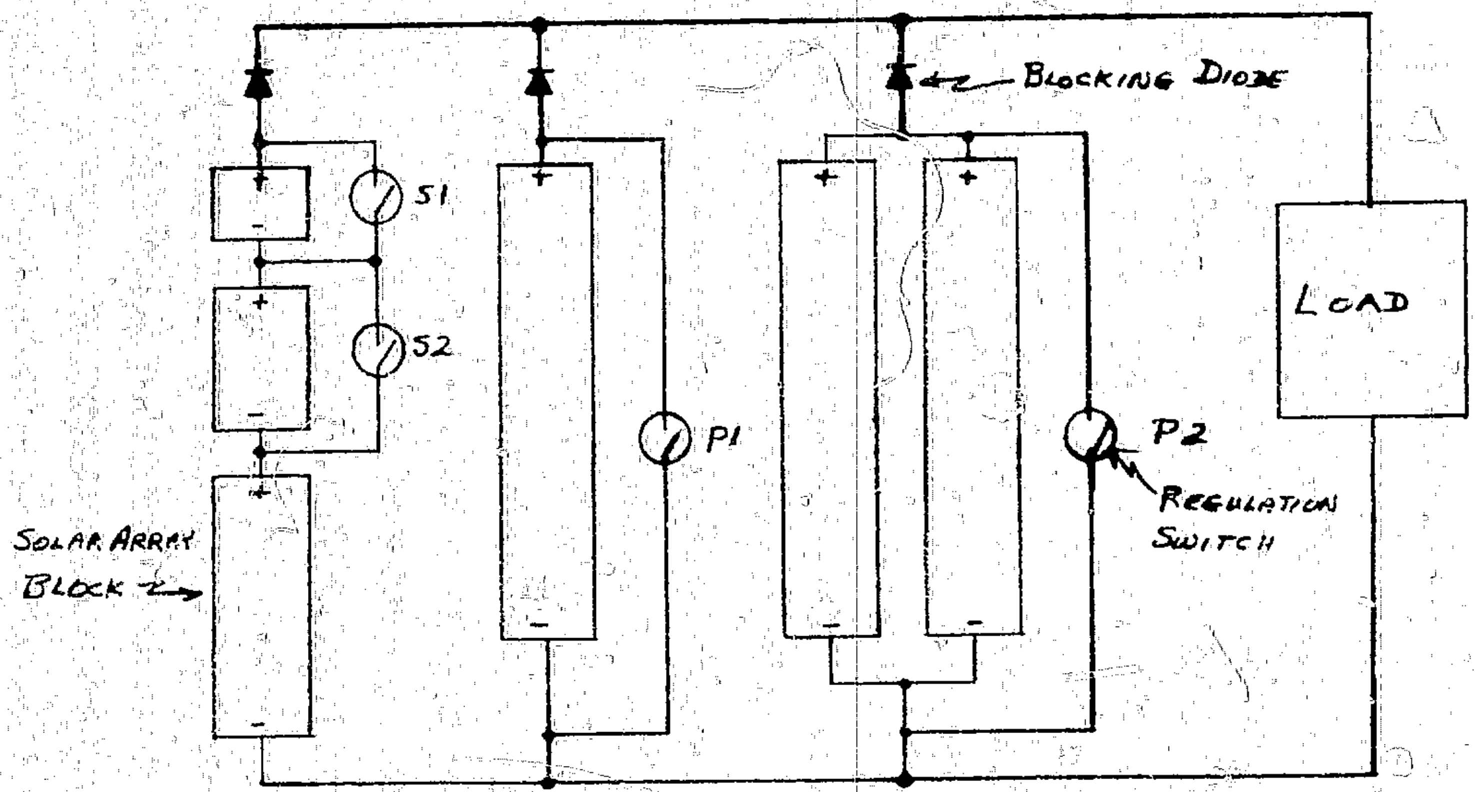
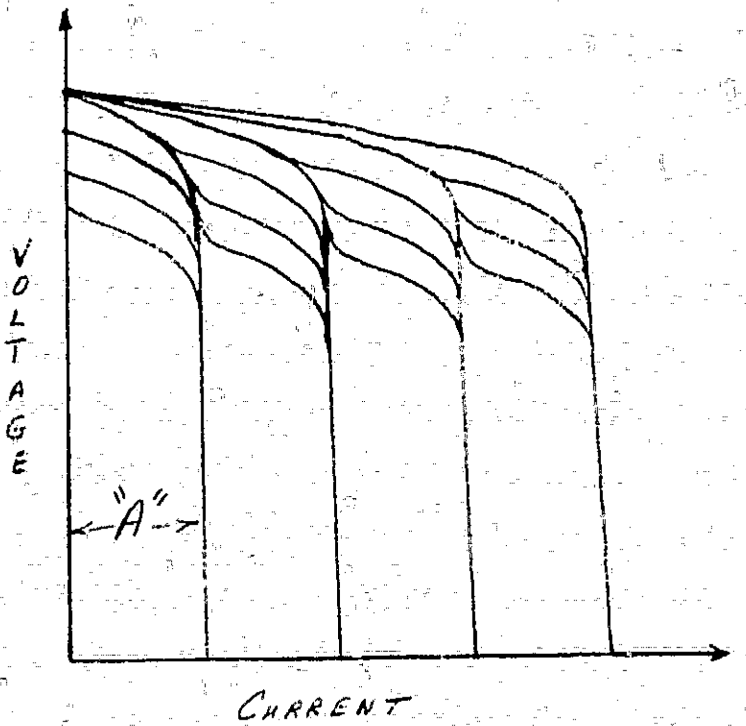
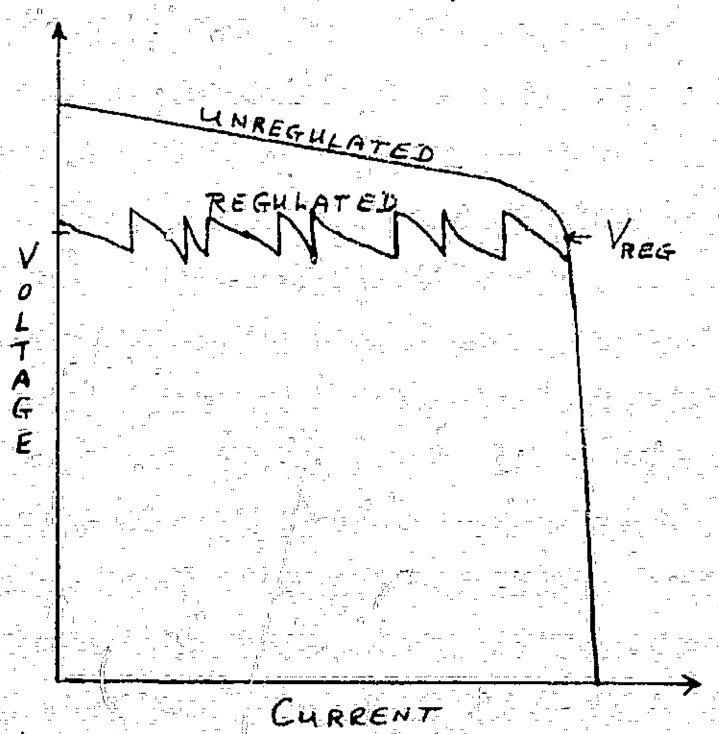


Figure 3. Simple Series/Parallel Regulated Solar Array



a)



b)

FIGURE 4 V-I CURVES FOR SIMPLE SERIES/PARALLEL REGULATED SOLAR ARRAY

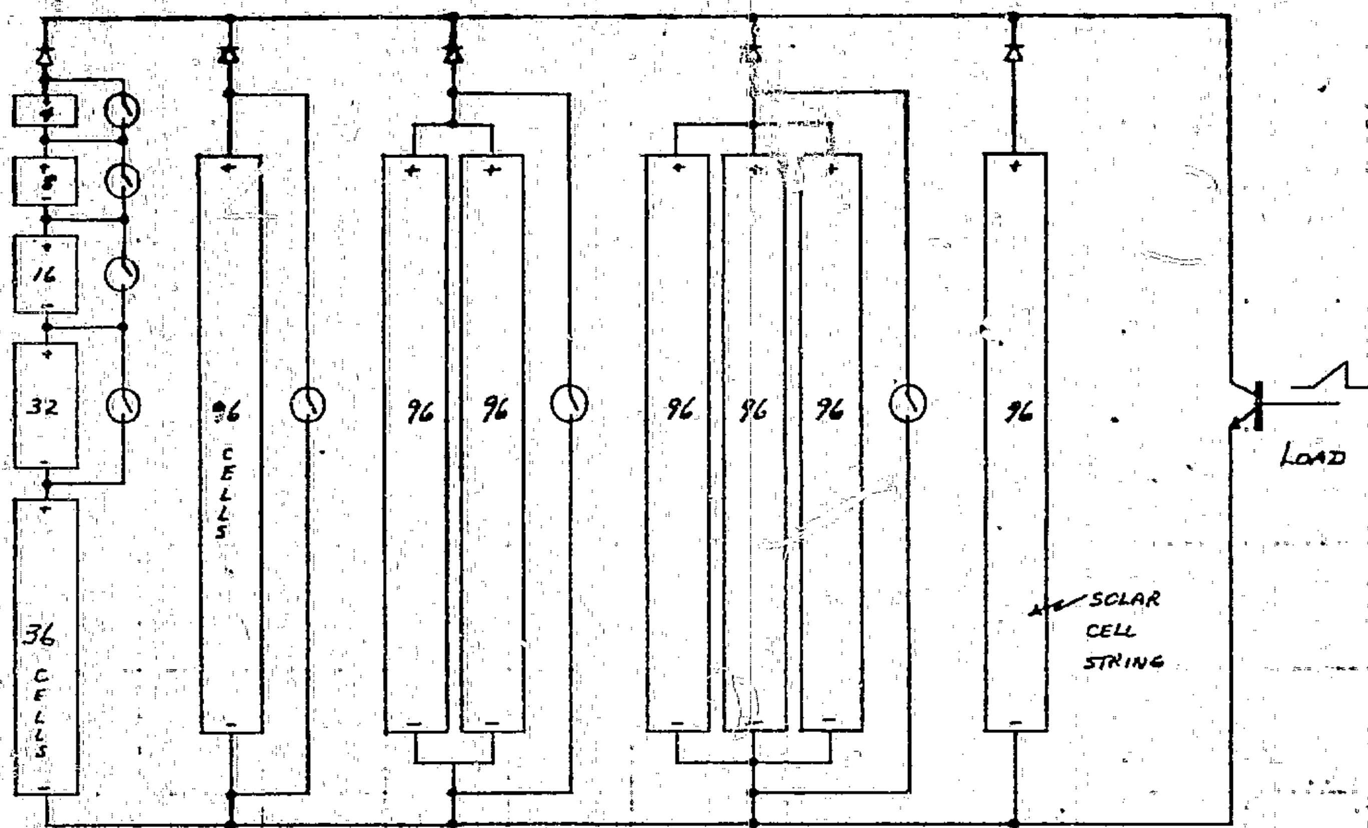


FIGURE 5. SERIES/PARALLEL REGULATED SOLAR ARRAY

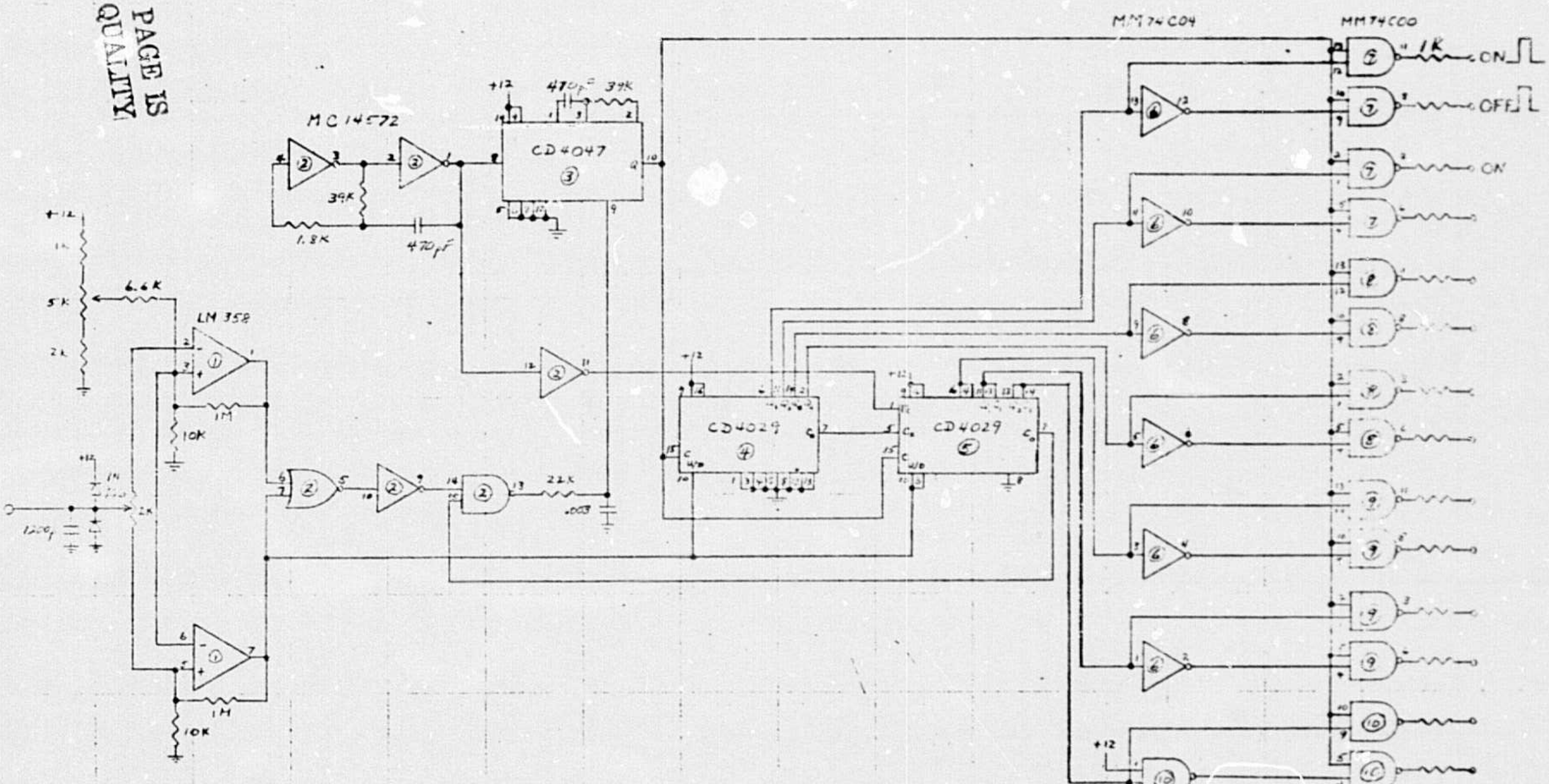


Figure 6. Solar Array Seven Switch Regulator

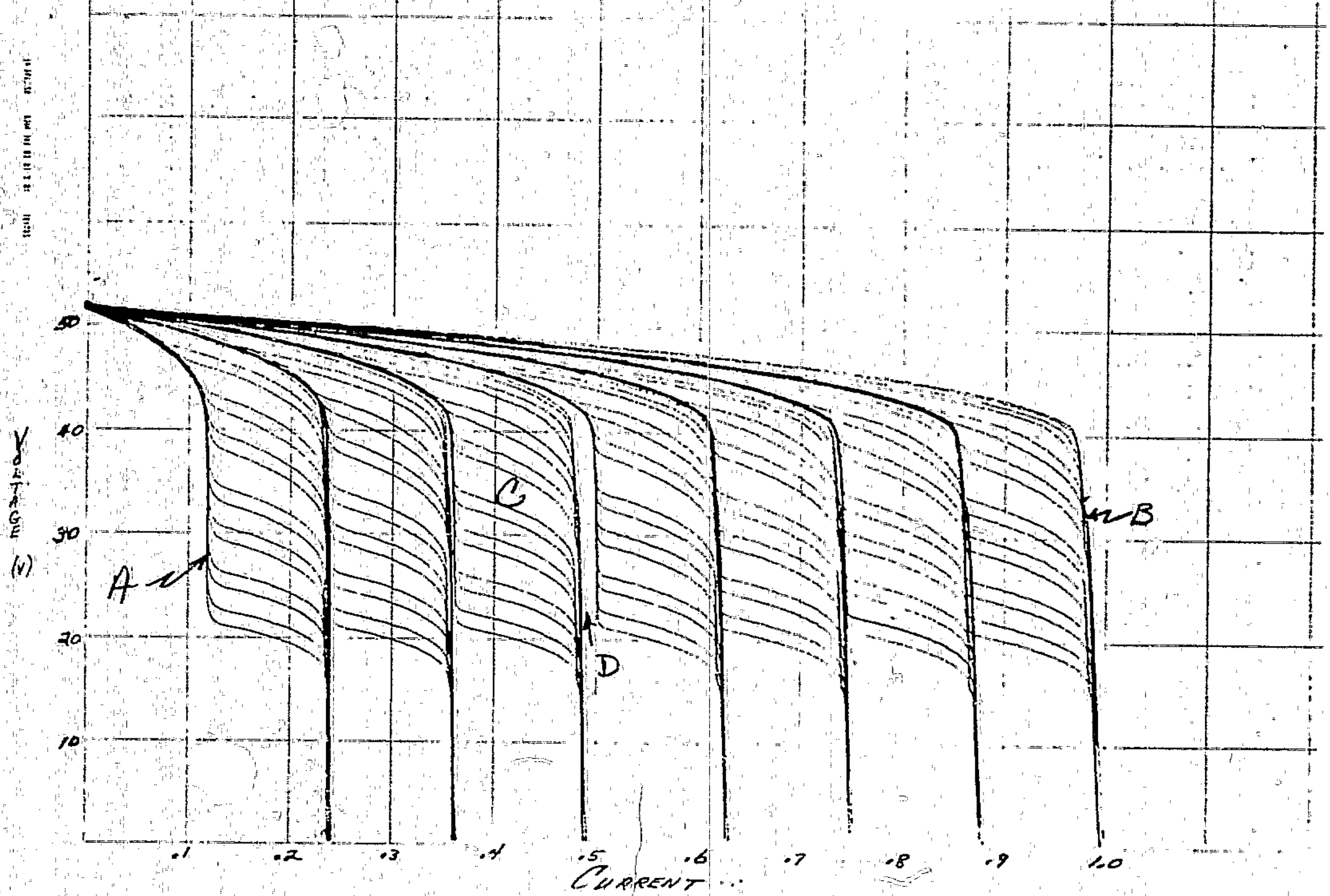


FIGURE 7. SOLAR ARRAY CHARACTERISTICS FOR VARIOUS SWITCHING COMBINATIONS

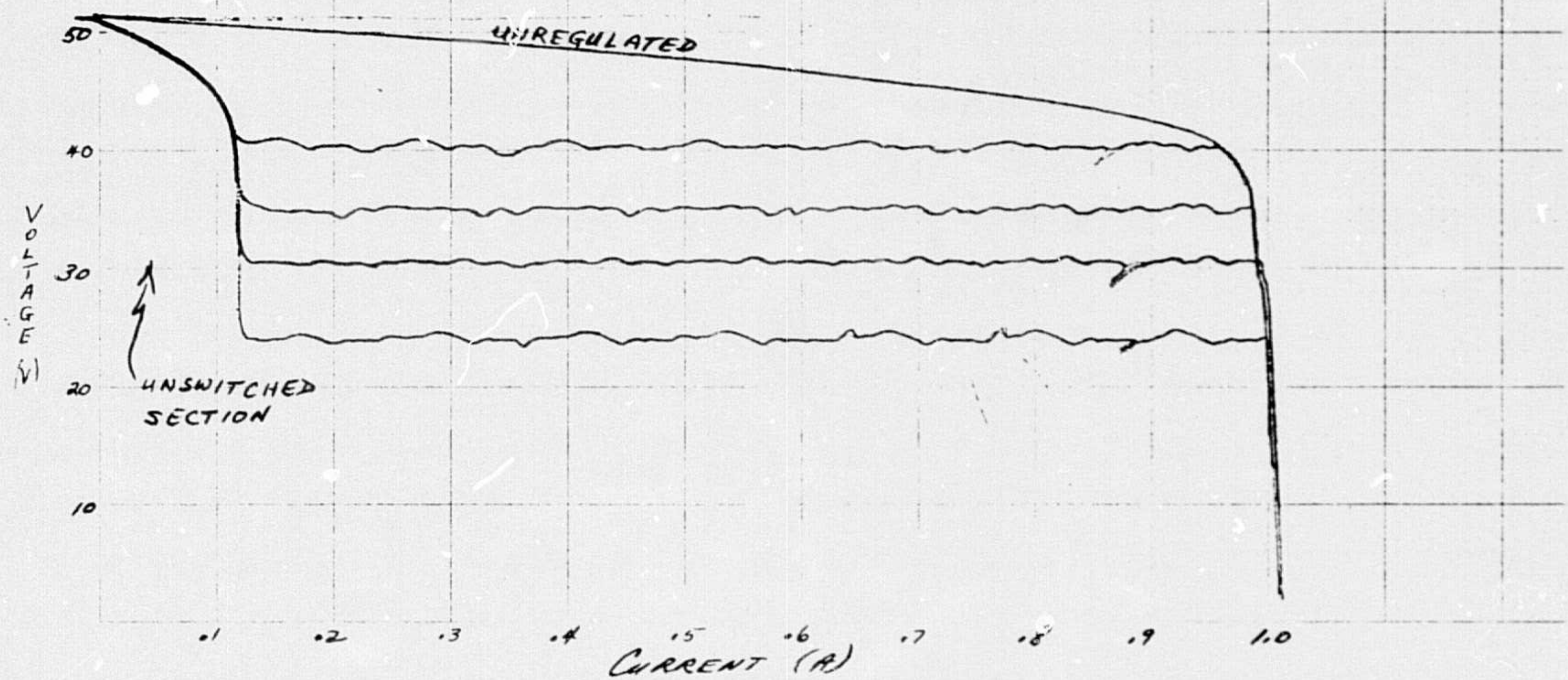


FIGURE 8. REGULATED SOLAR ARRAY CHARACTERISTICS FOR SEVERAL REGULATION SET-POINTS