X-636-65-259

DYNAMIC SOLAR CELL POWER SYSTEM SIMULATOR

BY

JOHN PAULKOVICH

JUNE 17, 1965

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-636-65-259

DYNAMIC SOLAR CELL POWER SYSTEM SIMULATOR

By
John Paulkovich

June 17, 1965

Goddard Space Flight Center
Greenbelt, Maryland

FOREWORD

The purpose of this document is to provide a method of simulating a solar cell power system for the evaluation of systems designed to operate from a solar cell power source. Simulation of solar array characteristics are discussed under static and dynamic conditions.

CONTENTS

LIST OF ILLUSTRATIONS

DYNAMIC SOLAR CELL POWER SYSTEM SIMULATOR

by

John Paulkovich

INTRODUCTION

Numerous circuits designed to operate from solar arrays (solar cell power systems) are evaluated by utilizing a power supply as the source. Although this is usually satisfactory, it does not present the same characteristic impedance to the circuit, and in many instances the circuit performance is hampered. For this reason it is very desirable to have a simulator to duplicate the characteristic impedance of a solar array source.

This paper describes a method of duplicating solar array characteristics to simulate various modes of operation. Solar array EI characteristics are not constant and vary as a function of temperature, angle of incidence and space environmental irradiation. It is desirable to simulate a solar array that has been exposed to these various conditions.

BASIC CIRCUIT

Since the EI characteristics of solar arrays resemble the EI characteristics of silicon diodes, then it is possible to utilize diodes to simulate the solar array. To illustrate, Figure 1 shows three typical EI characteristics of solar arrays and Figure 2 illustrates the EI characteristics of four types of silicon diodes. Although numerous diodes were tested the four diodes illustrated indicate the typical variations encountered in the EI characteristics. Comparing the general shape of the diode curves with the solar array curves indicates that the TIX442 and the 1N255 have the nearest EI characteristic curve resembling that of the solar arrays. The TIX442 was selected with intermingled 1N255's for slight squaring of the knee of the curve. These diode characteristics were plotted by using the circuit shown in Figure 3 and represents the basic circuit of the solar array simulator.

This circuit consists of a constant current regulator and a network of series connected diodes. Q1, Q2, R1, R2, and D1 compose the constant current regulator portion. R1 is used to set the ampere rate indicated by I_{sc}. Since I_{sc} is a constant current, then with the output terminals shorted this will be the short circuit current of the circuit simulating short circuit conditions on a solar array. With the output shorted $I_{sc} = I_o$. When the output terminals are open (no load) I_o will be zero and I_{sc} will still indicate what the short circuit current would be. This permits a continuous monitoring of the short circuit current even though the output is operating in some other mode.

Figure 4 illustrates a family of EI curves using the ckt of Figure 3. The curves show the output characteristics of the solar array simulator with 10 to 41 diodes. The curves were plotted with 10 diodes in series and then progressively adding two diodes at a time for each consecutive plot. Also shown is the arrangement of the shorting switches incorporated in the simulator for selecting the individual curves. The numerical sum of the switches in the "open" position are designated on the curves.

SIMULATION OF SATELLITE SPIN

During spacecraft operation an additional factor is added due to the satellite spin. Because of this spin, the solar paddles exhibit a modulation effect in the short circuit current caused by the change in the angle of incidence with respect to the sun. This effect also modulates the available solar array power. To simulate the ever changing angle of incidence on the solar paddles a method of modulating the short circuit current is necessary. Figure 5 illustrates a method whereby this is possible.

A low frequency oscillator is incorporated in this circuit. The purpose of this oscillator is to supply a modulated current (I_m) to the base resistor (R2). When resistor R2 is set to zero ohms the modulation current is bypassed and has neglibible effect on the constant current regulator. As this resistance is increased the constant current circuit is modulated. This in effect simulates satellite power fluctuations due to satellite spin.

CIRCUIT OPERATION

Figure 6 illustrates a complete schematic of the solar array simulator. Diodes D1 through D41 form the series diode string which determine the EI output characteristics of the simulator. As mentioned previously, the diodes are arranged such that if all the switches are closed there will be 10 diodes in the output circuit. The switches add groups of diodes in a binary order, that is, 1, 2, 4, etc., this permits adding up to 31 diodes to the ten that are already in the circuit for a total of 41 diodes. If the short circuit current adjustment is set for 2 amperes, then the diodes average approximately .9 volts each. Thus the open circuit voltage is adjustable in approximately .9 volt steps and places the maximum output open circuit voltage at approximately 37 volts. This was considered ample for our purposes. The lowest open circuit voltage at two amperes diode current is approximately 9 volts. This range can readily be altered to suit the individual requirements.

Resistors R1 and R2 adjust the short circuit current. The range of control is from 100 ma. to two amperes. Transistors Q1, Q2, and Q3 form a phase shift oscillator as the modulation source. Frequency determining capacitors C1, C2, and C3 are mounted on a three pole three position wafer switch. These groups of (3) capacitors were selected for frequencies of 7 cycles per minute, two cycles per second and ten cycles per second. This oscillator produces a sine wave output, a portion of which is fed to the modulation transistor Q4. The collector load of Q4 (R20) was selected so that approximately 60% modulation will occur if the entire resistance is in the circuit, thus permitting modulation control from zero to 60%. The percent of modulation is therefore directly proportional to the resistance setting of R20 over the limits of the control. The low frequency position (7 cycles per min.) is used to set up the desired modulation. This frequency was selected to be slow enough so that the short circuit current ammeter would respond to the modulation for initial adjustment purposes. Two cycles per second was selected as the typical modulation frequency encountered in space satellites and an arbitrary 10 cycles per second was selected just to have a higher than normal rate.

Transistor Q9 and diode D44 supply a constant current to the modulation and current reference circuit over a wide range of input power supply voltage swing.

Figure 7 illustrates the unit assembled on a 19 inch rack panel. Three meters are visible, a voltmeter and two ammeters. A three position switch located adjacent to the voltmeter selects the voltage to be monitored. The first position of the switch places the voltmeter across the input terminals to measure the power supply voltage. The second position monitors the collector to emitter voltage of transistor Q8 and the last position monitors the output voltage of the simulator. The center meter indicates the short circuit current and the lower meter indicates the output current.

Two short circuit current adjustment controls are incorporated. These controls (R1, R2) are in series and are designated "coarse adj" and "fine adj" and determine the short circuit current indicated on the center meter.

The graph shown on the panel is a family of curves similar to Figure 4. The graph is adjustable in that it can slide either to the right or left while the amps and volts scale remain stationary. The purpose of this is to be able to set the short circuit current to the desired ampere rate and thus be able to select the curve with the desired open circuit voltage. The individual curves are designated 0, 2, 4, 6, etc. These correspond to the sum of the switches turned "on" (diodes unshorted) thus adding the designated number of diodes. Although the curves on the chart are with pairs of diodes added it is possible to add just one diode at a time to simulate conditions one half way in between those curves illustrated.

Once a desired curve is selected the appropriate switches are switched to the "in" position and the short circuit current is set to the desired ampere rate. The output EI characteristics will then be identical to that portion of the selected curve within the frame on the chart.

ALTERING THE OUTPUT EI CHARACTERISTICS

It may be desirable to add additional slope to the diode EI curves to simulate a degraded solar array. Figure 8 illustrates a family of curves using ten diodes in series and the effects of shunting resistors across this entire group. Resistances of 200, 100, 50 and 30 ohms were shunted across the diode string and the family of curves plotted. These curves indicate that the greatest change in the slope occurs in that portion of the curve nearest to the short circuit current. Figure 9 illustrates the location of the shunt resistor (R_{sh}).

Adding resistance in series with the output affects that portion of the curve nearest to the open circuit voltage as indicated in Figure 10. The curves illustrate the effect of adding resistances of zero, 1, 2, and 3 ohms (R_{ser} Figure 9).

Figure 11 illustrates the output of the solar array simulator compared to a solar paddle EI curve. The EI characteristic of the simulator duplicates the paddle curve very closely and little or no slope correction is necessary. Figure 12 illustrates a solar paddle whose EI characteristic does not coincide with the solar array simulator. The greatest correction is necessary in that portion of the curve nearest to the open circuit voltage. A correction of approximately .5 volts is necessary at .5 amperes or

$$R_{ser} = \frac{\Delta E}{\Delta I} = \frac{.5}{.5} = 1 \text{ ohm}$$

with a 1 ohm resistor added to the output, the EI plot coincides very nicely with the desired plot. Figure 13 compares the output of the solar array simulator with a solar array EI plot where the simulator requires correction in that portion of the curve nearest to the short circuit current. From the graph:

$$R_{sh} = \frac{\Delta E}{\Delta I} = \frac{15}{.08} = 188 \text{ ohms}$$

188 ohms added across the output terminals of the solar array simulator corrects the slope as shown in Figure 13.

It is also possible to closely simulate a solar array EI characteristic when given the open circuit voltage, short circuit current and the peak power point voltage and current. The procedure described above could be used to shift the peak power point of the solar array simulator to that of the desired solar array characteristic curve.

As an example:

Given:

Open circuit voltage = 20 volts

Short circuit current = 1.5 amperes

Peak power point = 13.5 volts, 1.25 amperes

The solar array simulator is set for 1.5 amperes short circuit current. To determine the open circuit voltage slide the chart on the simulator until the short circuit current coincides with 1.5 amperes. From the voltage scale select the appropriate curve for 20 volts open circuit voltage. This curve is labled 14 and means that a combination of switches must be selected to give a total of 14. Therefore switches 2, 4, and 8 would be switched to the "in" position. A reproduction of a portion of curve 14 is illustrated in Figure 14.

The method of determining the series resistor (R_{ser}) and shunt resistance (R_{sh}) necessary for correcting the EI characteristics of the solar array simulator is also shown in Figure 14. The series resistance should be:

$$R_{ser} = \frac{\Delta E}{I_p}$$

where I_p = peak power point current and ΔE is the difference in voltage between curve 14 and the peak power point voltage. Thus from Figure 14:

$$R_{ser} = \frac{2.5}{1.25} = 2 \text{ ohms}$$

The shunt resistance necessary will be:

$$R_{sh} = \frac{E_P}{\Delta I}$$

where E_p = voltage at the peak power point and ΔI is the current difference between curve 14 and the peak power point current. Then:

$$R_{sh} = \frac{13.5 \text{ volts}}{.2 \text{ amperes}} = 67.5 \text{ ohms}$$

The dotted plot of Figure 14 illustrates the corrected plot when R_{ser} = 2 ohms and R_{sh} = 67.5 ohms.

CONCLUSION

We have shown that with the proper selection of series diodes it is possible to simulate a solar cell power system where at the beginning of satellite launch little or no correction will be required to the solar array simulator. With the proper selection of R_{ser} and R_{sh} it is possible to degrade the solar array simulator characteristics to simulate a solar cell power system after being subjected to space environmental conditions providing that the EI characteristics of the solar cell power system can be anticipated. In addition the circuit is capable of simulating the dynamic conditions encountered during satellite spin by modulating the output EI characteristics. This unit should fulfill the simulation of the major EI characteristic variations anticipated in solar cell power systems.

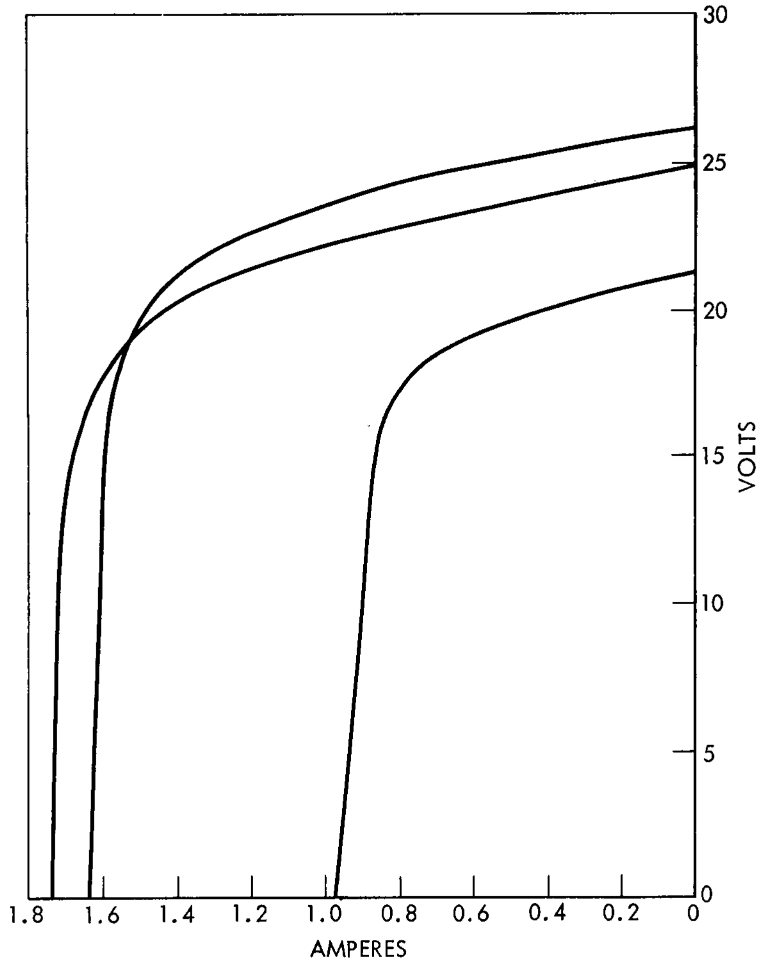

Figure 1 - Typical Solar Cell Power System Ei Characteristics

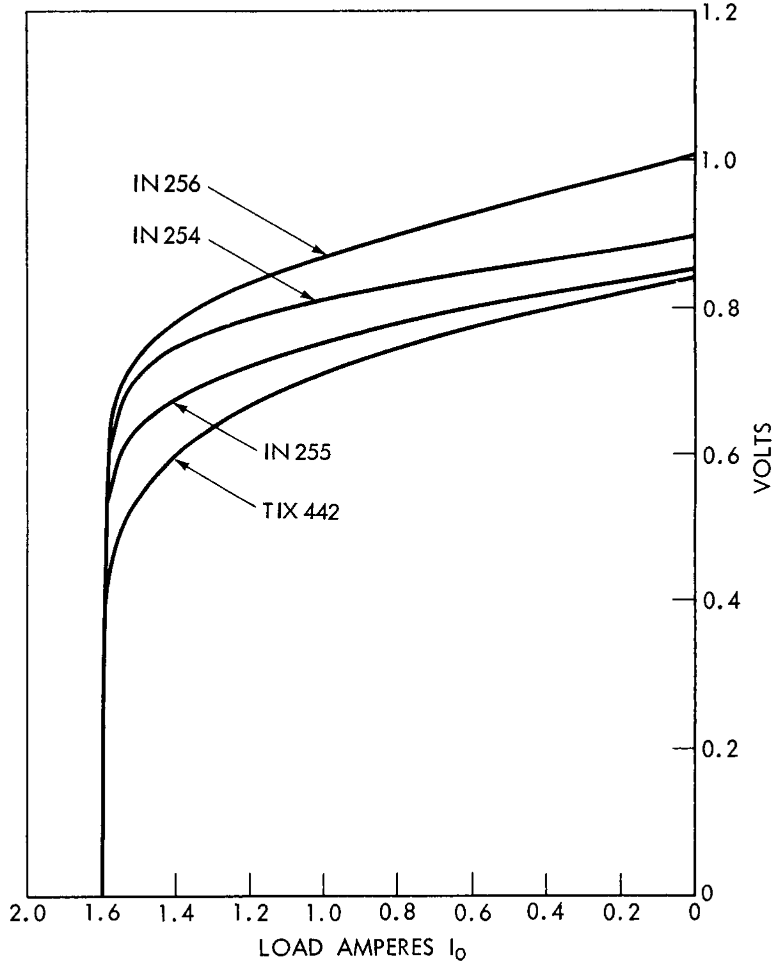

Figure 2 - Typical Diode Characteristics

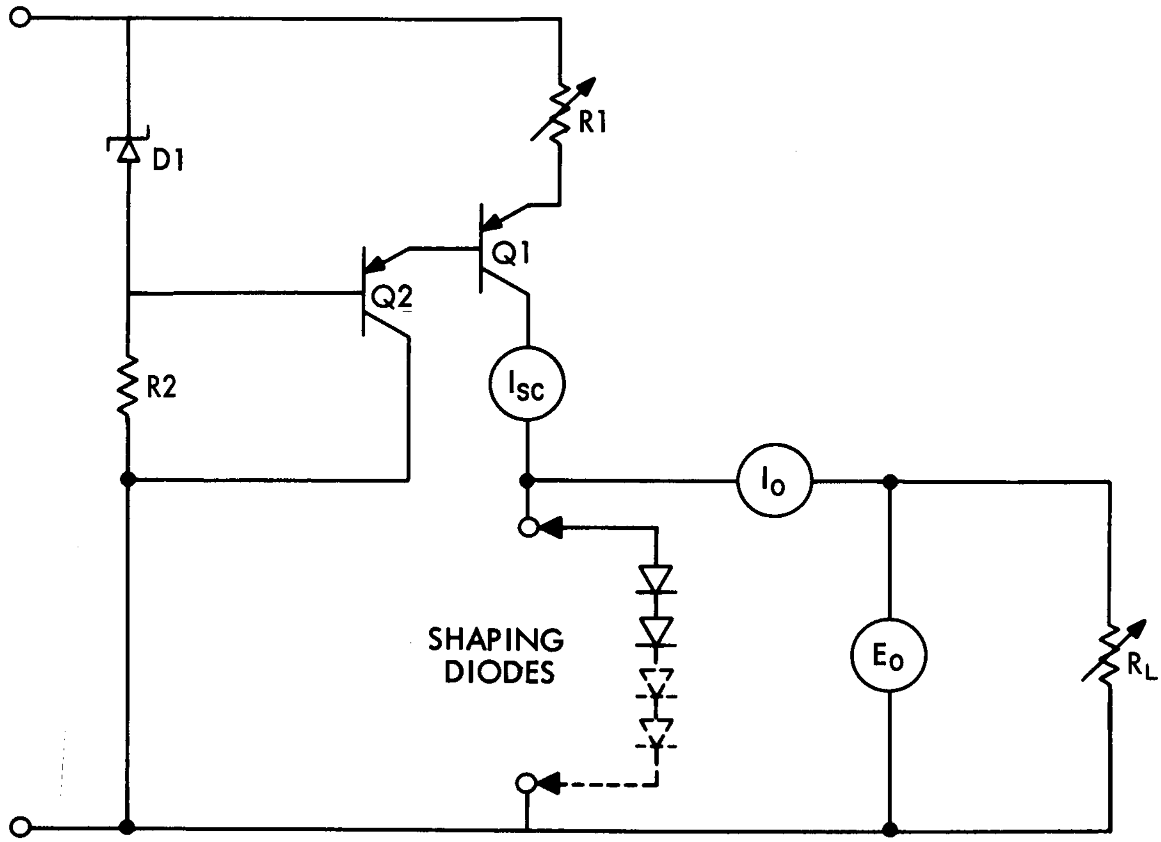

Figure 3 - Basic Circuit of the Solar Array Simulator

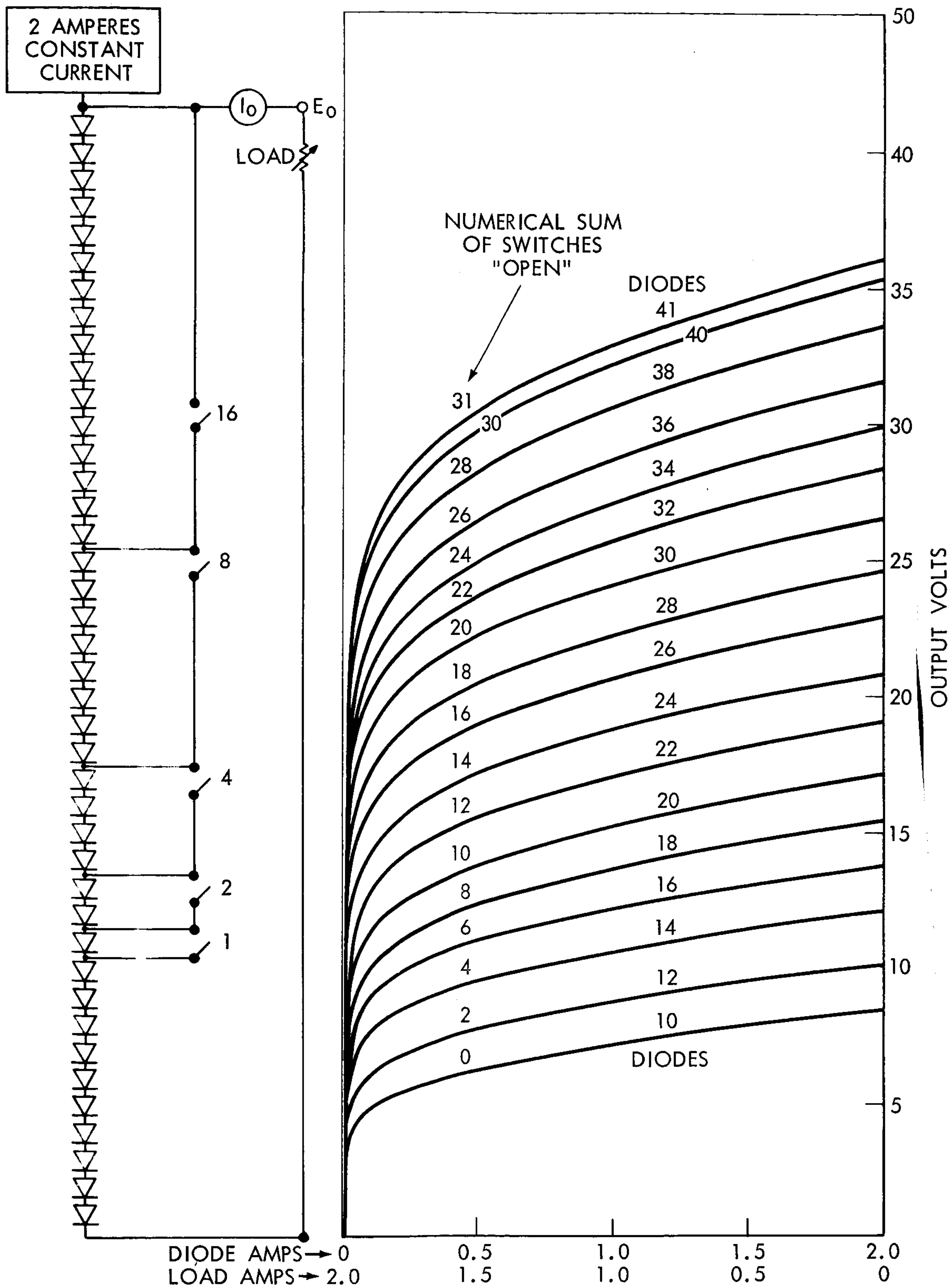

Figure 4 - EI Output Characteristics of the Solar Array Simulator

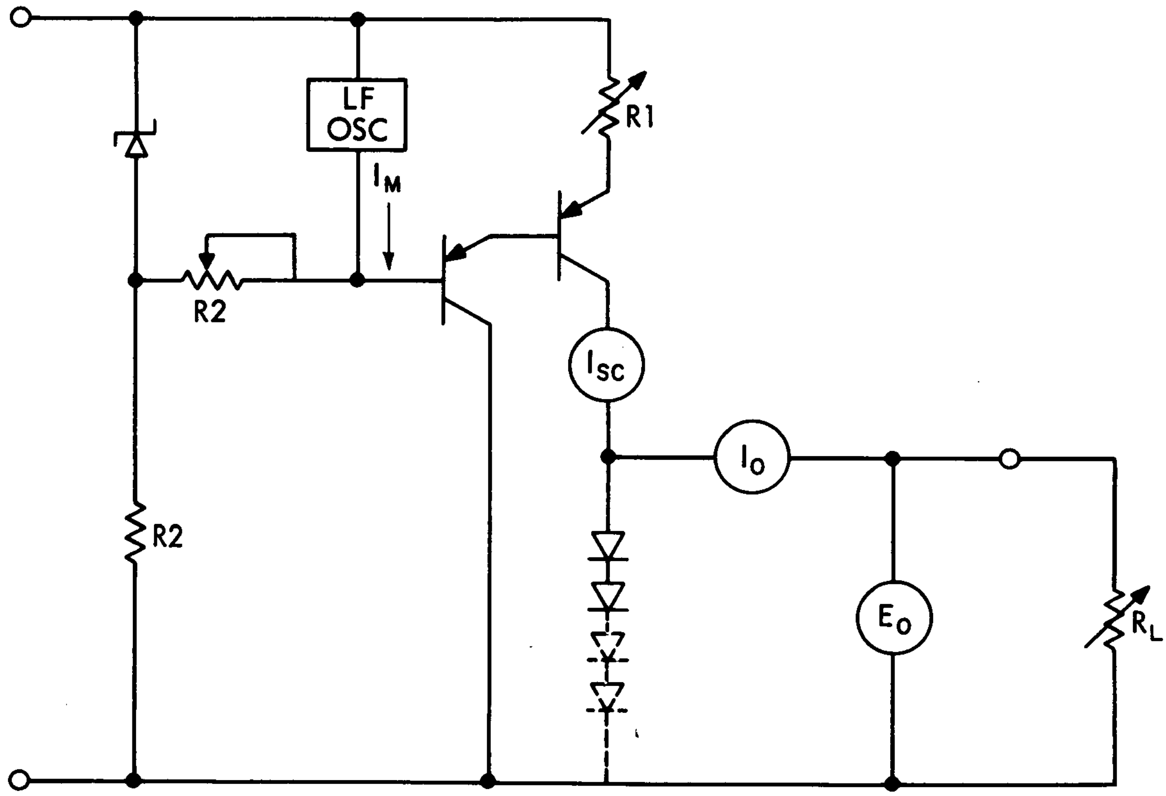

Figure 5 - Satellite Spin Simulation by Modulation of the Short Circuit Current

Table 1

R_1	43Ω, 1 W	
R_2	13Ω, 1W	
R_3	16K, 1/4 W	
R_4	4.3K, 1/4 W	
R_5, R_6	20Ω, 1/2 W	
C_1, C_2	25 uf, 125 VDC electrolytic	
D_1 -D_4	UTR 42 Unitrode Corporation	
Q_1, Q_2	2 N 2850-2	Solid State Products, Inc.
Q_3, Q_4	2 N 2034	Silicon Transistor Corporation
Q_5, Q_6	2 N 2580	Delco
T_1	Core # 50076-1A Magnetics, Inc., Primary winding 20 turns center-tapped #16 A.W.G. wire, feedback winding 8 turns center-tapped #30 A.W.G. wire, secondary winding 480 turns center-tapped #28 A.W.G. wire.	
T_2	Core #50168-1D Magnetics, Inc. Primary winding 2622 turns center-tapped #36 A.W.G. wire, feedback winding 1050 turns center tapped #36 A.W.G. wire, secondary winding 525 turns each #36 A.W.G. wire	

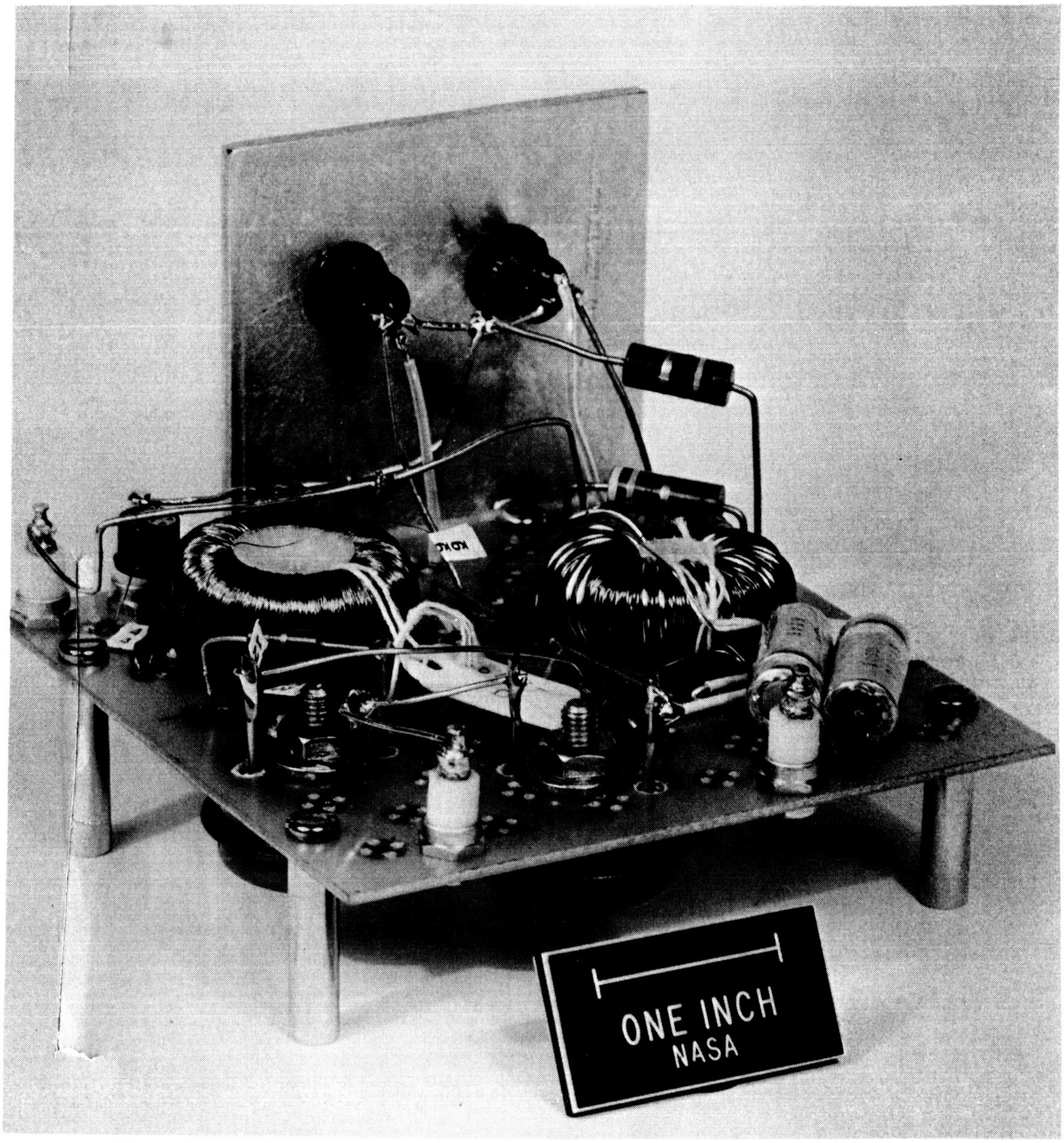

Figure 9—Breadboard Model of Inverter

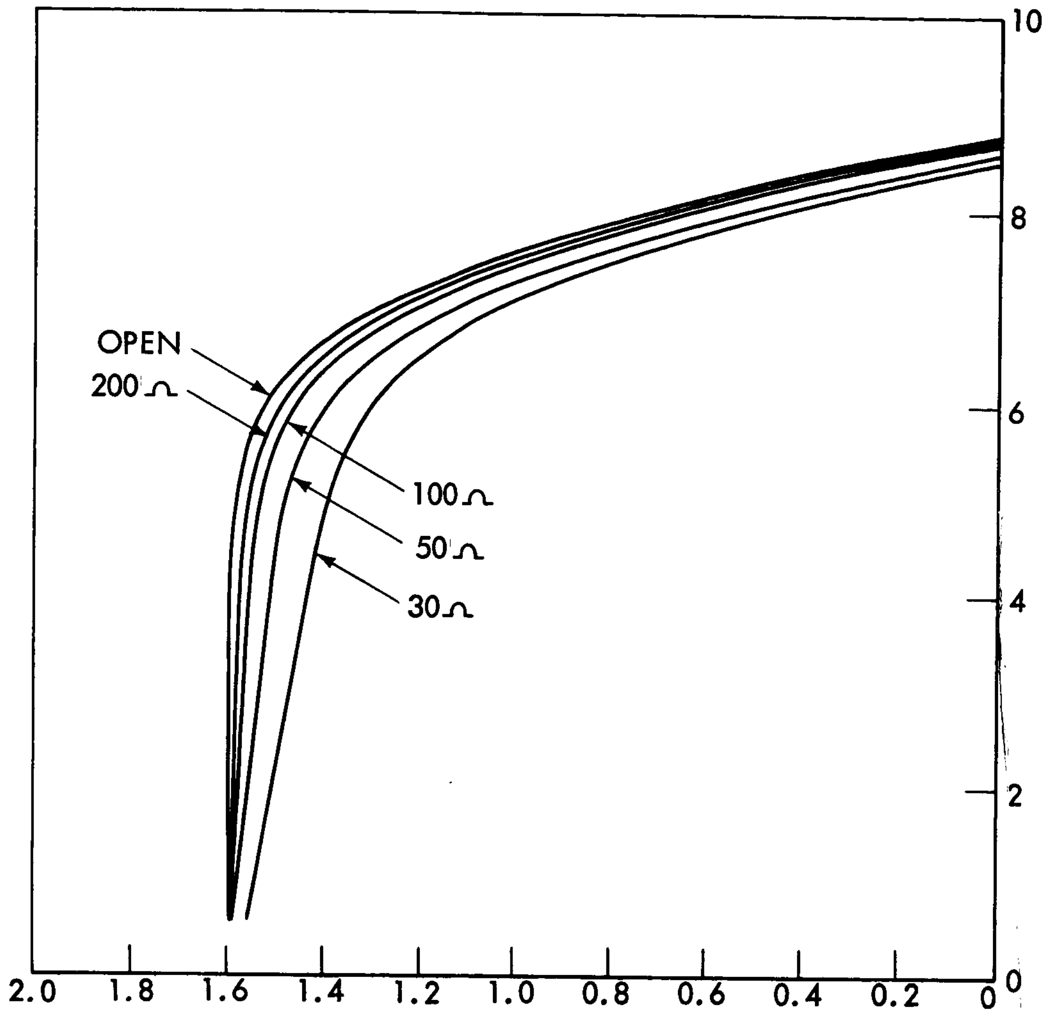

Figure 8 - Effect of Shunt Resistance on the Solar Array Simulator

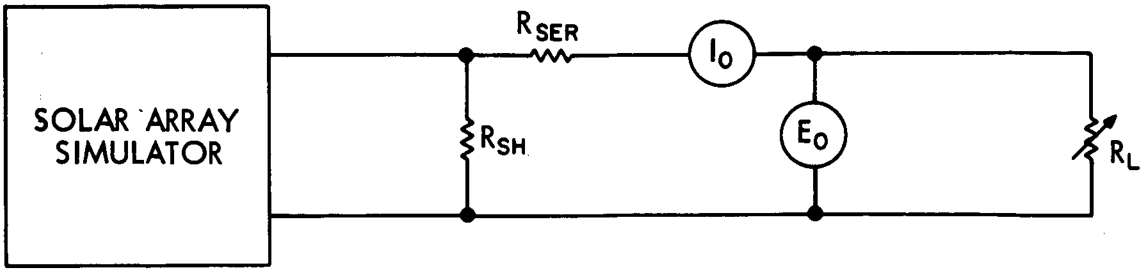

Figure 9 - Test Setup for Altering the Output Characteristics of the Solar Array Simulator

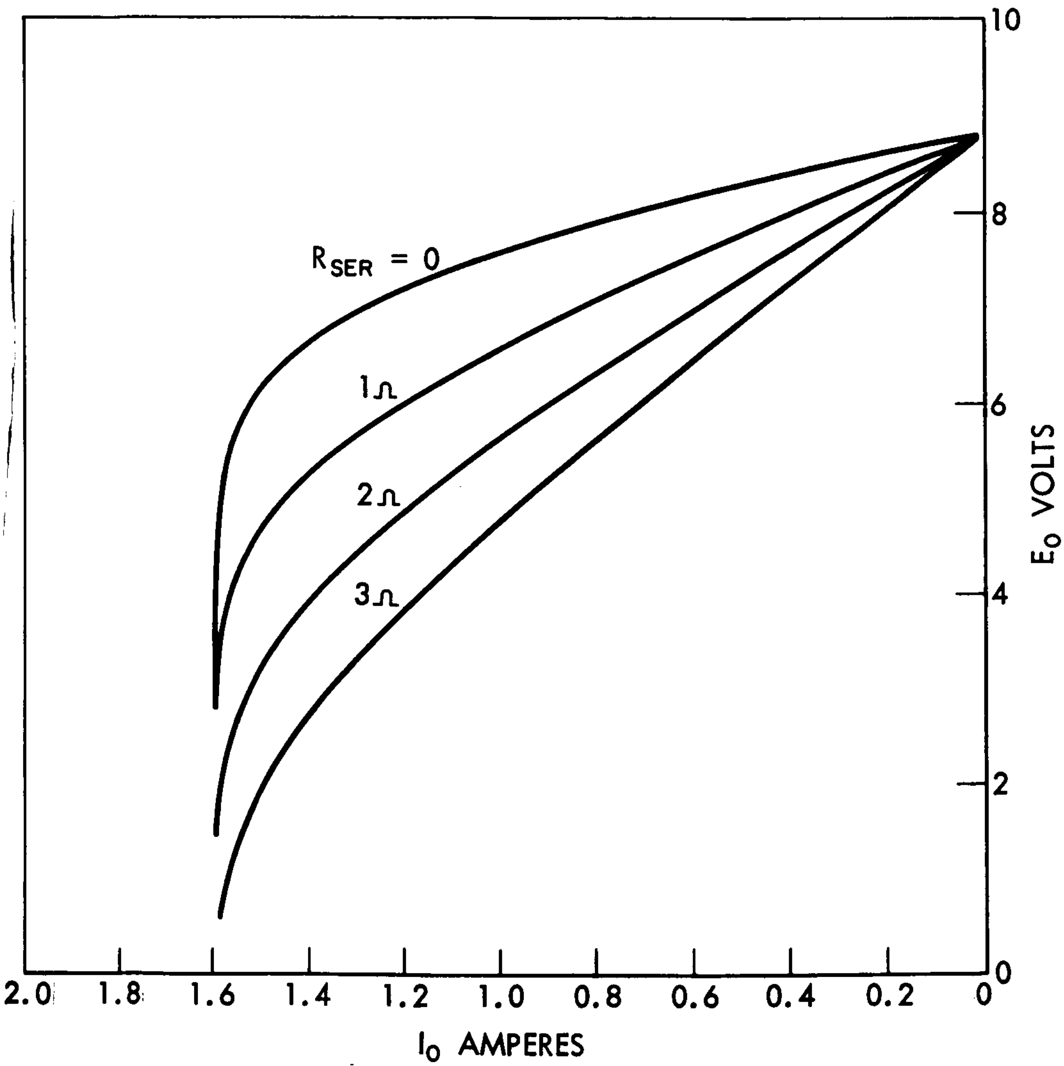

Figure 10 - Effect of Series Resistance on the Solar Array Simulator

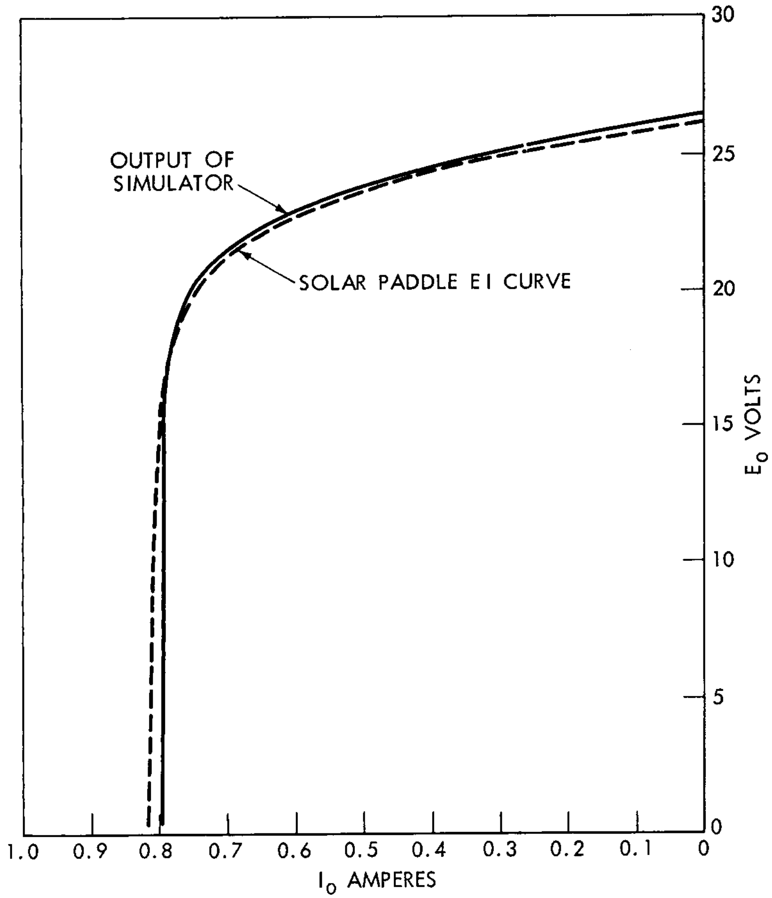

Figure 11 - EI Characteristics of the Simulator Compared to a Typical Solar Paddle

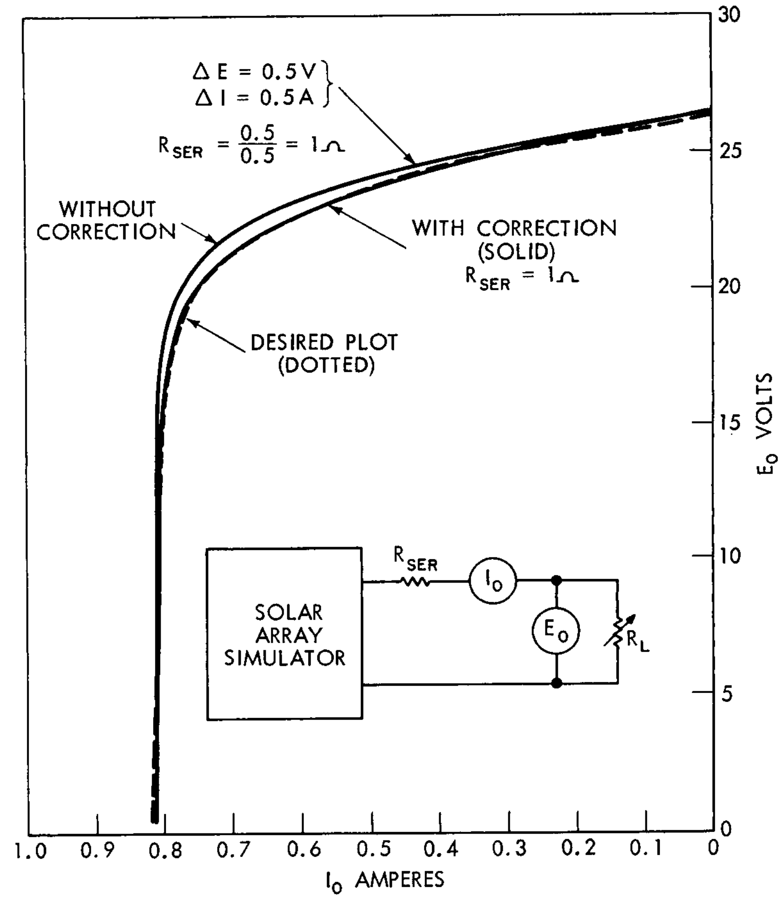

Figure 12 - Output of Solar Array Simulator Compared to a Typical Solar Paddle whose EI Characteristics do not Coincide with the Simulator

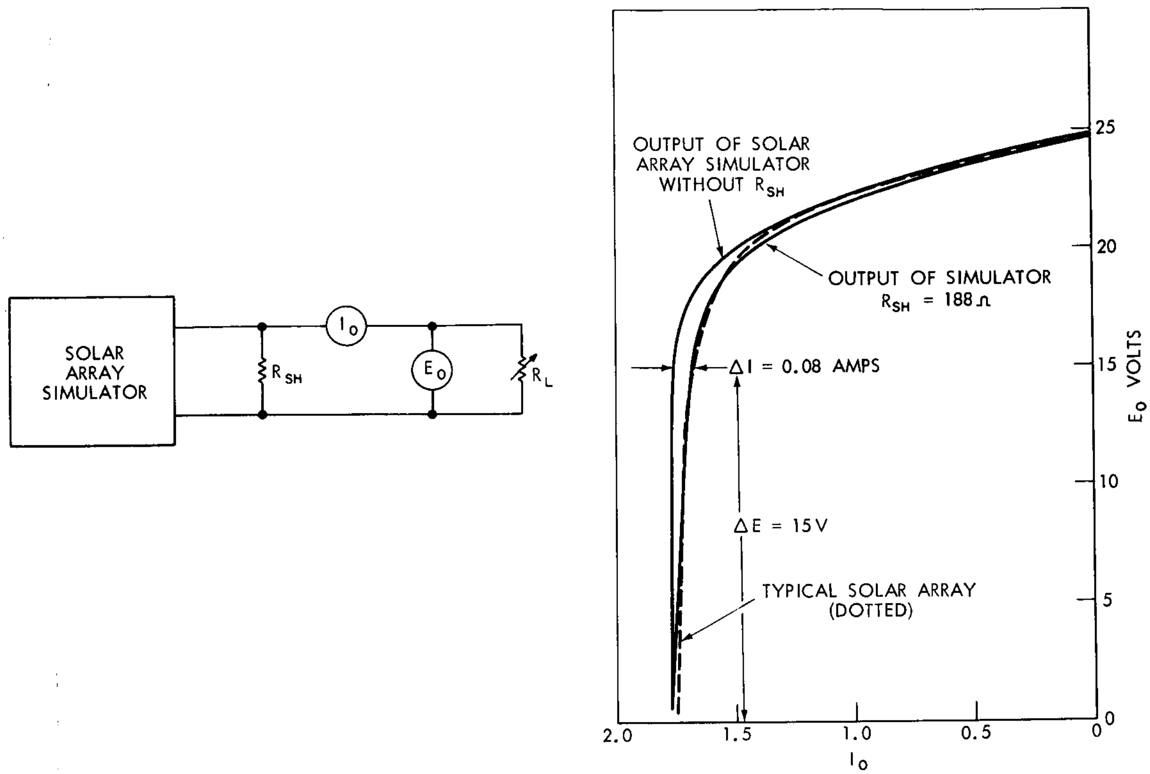

Figure 13 - Correcting That Portion of the Curve Nearest the Short Circuit Current

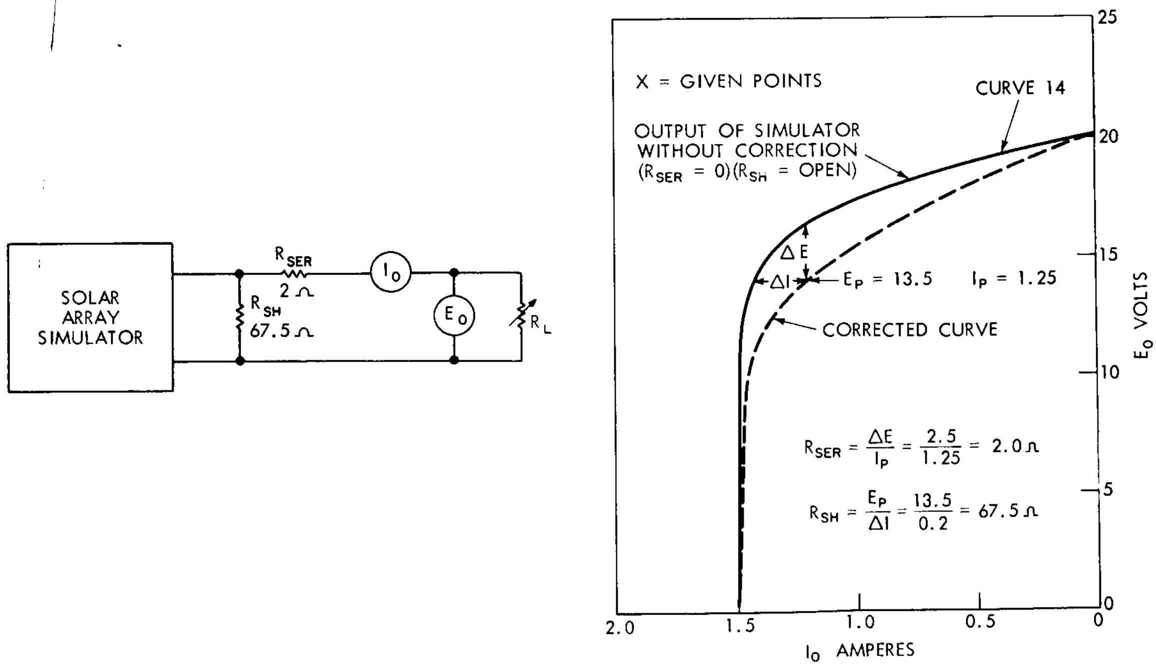

Figure 14 - Simulating the EI Characteristics When Given "Open Circuit Voltage", "Short Circuit Current" and the "Peak Power Point"