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A HIGH POWER CURRENT–VOLTAGE CURVE TRACER EMPLOYING A CAPACITIVE LOAD*

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Summary

A portable photovoltaic voltage *versus* current curve tracer is discussed. The curve tracer employs a capacitive load to provide automatic sweeping of the array voltage. The unit is capable of measuring arrays of up to 10 kW in power but is smaller and lighter than a conventional 2.5 kW dissipative load.

1. Introduction

The current *versus* voltage ($I-V$) plot of a photovoltaic array or module is a powerful diagnostic aid. Many recently built photovoltaic installations are in remote locations, which presents the problem of transporting bulky testing equipment. As photovoltaic power becomes more common, a service industry will be needed to develop and supply portable diagnostic instruments capable of measuring modules or entire arrays. Extensions of the present steady state dissipative methods for making $I-V$ curves will not be adequate to fill these needs.

A very small and light curve tracer employing a capacitive load can be made. The basic concept is quite simple, as shown in Fig. 1. Initially, the switch is closed, the capacitor is discharged and the array is operating at short circuit. When the switch is opened, the array current flows into the

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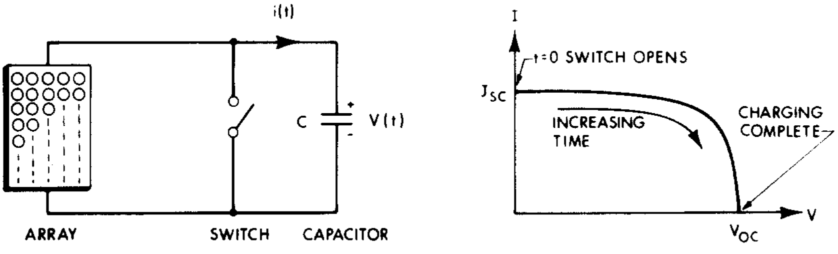

(a) (b)

Fig. 1. Use of a capacitor to measure the I–V curve: (a) basic capacitive charging method and (b) resultant I–V curve using

$$V(t) = \frac{1}{C}\int_0^t i(\tau)\,d\tau$$

capacitor and charges it according to the following familiar capacitor equation:

$$V_C(t) = \frac{1}{C}\int_0^t i(\tau)\,d\tau \tag{1}$$

As the charging progresses, a data acquisition system measures the voltage and current of the array and plots them parametrically.

2. Design considerations

2.1. Capacitor sizing

This measurement scheme hinges on finding a suitable capacitor. If the array is assumed to have a fill factor of unity, eqn. (1) can be solved easily. The voltage simply ramps up from zero to the open-circuit voltage V_{oc} in a time T_{scan}. When the array reaches V_{oc}, the current drops to zero and the charging stops:

$$V_{oc} = \frac{I_{sc}}{C}T_{scan} \tag{2}$$

This equation can be rearranged to find the capacitor size necessary to produce a predetermined scan time:

$$C = \frac{I_{sc}}{V_{oc}}T_{scan} \tag{3}$$

Equation (3) shows that the ratio of the short-circuit current to the open-circuit voltage is more important than the array power in determining the capacitor size. A minimum scan time should be determined such that the "transient I–V curve" very closely approximates the I–V curve obtained using "steady state methods". The large area pulsed solar simulator (manufactured by Spectrolab Inc.) obtains good results with scan times of 2 ms. If a 2000 μF capacitor is chosen, the curve tracer will be able to handle any module or array provided that

$$\frac{I_{sc}}{V_{oc}} \leqslant 1 \tag{4}$$

This includes all residential arrays and the newer low voltage, high current module designs. 1000 μF, 450 V capacitors are available from many manufacturers and are about the size of a 12 fl oz soft drinks can.

2.2. Power dissipation

The reason why conventional I–V loads are so heavy and bulky is the need for large heat sinks and fans to dissipate the array power. The capacitor charging curve tracer has a very low average power dissipation that depends only on the capacitor size, the open-circuit voltage and the frequency f_m of measurement:

$$P_{avg} = \frac{1}{2} f_m C V_{oc}^2$$

For example, a 5 kW array at 250 V which is measured every 3 s would require an average power dissipation of only 21 W with a 2000 μF capacitor.

3. Implementation

The curve tracer consists of two units (Fig. 2). The curve acquisition unit (CAU) contains all the power electronics, data acquisition and short-term memory together with control electronics to run the measurement. The data display, storage and analysis are performed by a Hewlett–Packard model 85 desk-top computer. The CAU and Hewlett–Packard 85 computer communicate via an IEEE 488 instrumentation bus.

A block diagram of the system is shown in Fig. 3. Initially, switch 1 is closed and switches 2 and 3 are open. This allows the capacitor to be charged to a negative voltage. When switch 1 is opened and switch 2 is closed, a negative voltage will be placed across the array. The I–V curve will actually start in the reverse bias region, proceed through short circuit and continue all the way to open circuit. In this manner the entire forward operating characteristic can be plotted. Once the curve is complete, switch 2 is opened and switch 3 is closed to discharge the capacitor for the next measurement.

During the capacitor charge-up, the CAU quantizes the voltage and current with 8-bit resolution and stores them in a temporary memory. The range selection is chosen such that I_{sc} and V_{oc} can always be made to lie above 80% of the full-scale value. This makes full use of the analog-to-digital converter range and reduces quantization errors. When the CAU is idle, it performs an autozero function.

Fig. 2. Photograph of a 10 kW curve tracer showing the CAU (right) and a Hewlett Packard 85 computer.

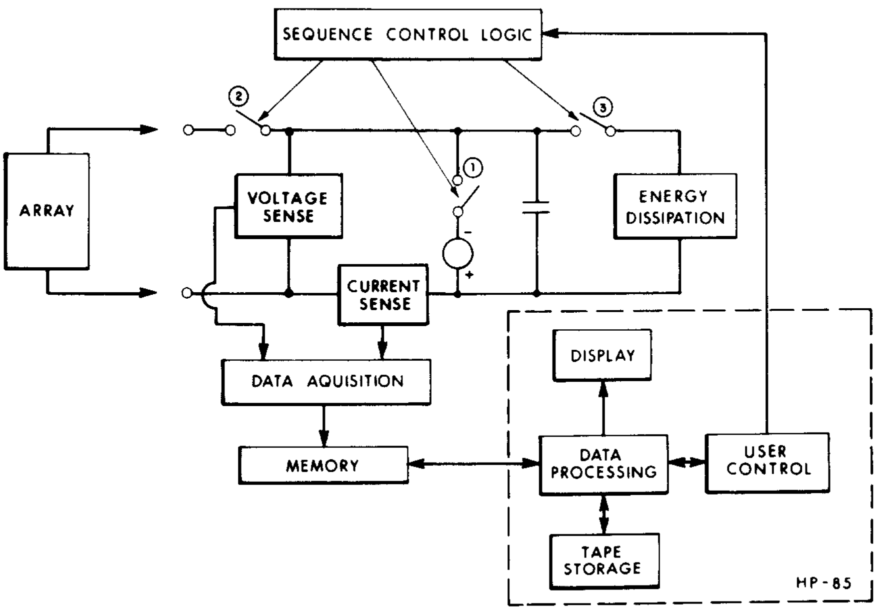

Fig. 3. Simplified block diagram of an I–V curve tracer.

The Hewlett–Packard 85 computer is not fast enough to run the measurement directly, so it must wait until the curve is complete and then read the data from the temporary memory in the CAU. Data display, hard copy and magnetic tape storage are all performed by the computer. On-screen prompting and menu format are used to minimize operator errors. All the commands to the CAU are generated by the Hewlett–Packard 85 computer and are transparent to the user. A comparison of the $I-V$ curves taken with the capacitive load and those plotted for a more conventional dissipative load is presented in Fig. 4. The curves agree closely, indicating that fast scan times are possible and can be used to locate faults in large arrays.

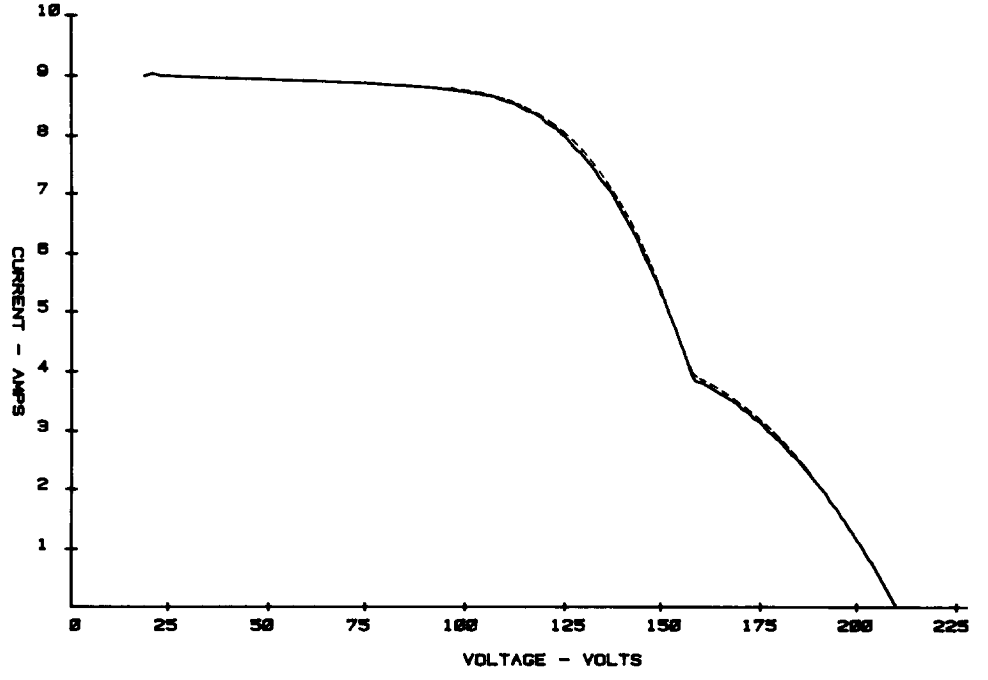

Fig. 4. Output of a capacitor load curve tracer (——) and a resistor load (— — —) (ambient temperature, 32.0 °C; cell temperature, 50.0 °C; insolation, 80.0 mW cm^{-2}; V_{oc} = 211 V; I_{sc} = 9.17 A; P_{max} = 1025 W (126 V, 8.10 A)).

Figure 5 shows an $I-V$ curve of an array with a maximum power point of approximately 7 kW, which could not be measured with a commercially available resistive load.

A comparison of the physical dimensions of the capacitive load with a resistive load of equal rating (10 kW) is shown in Table 1. The capacitive load is far smaller, lighter and less expensive.

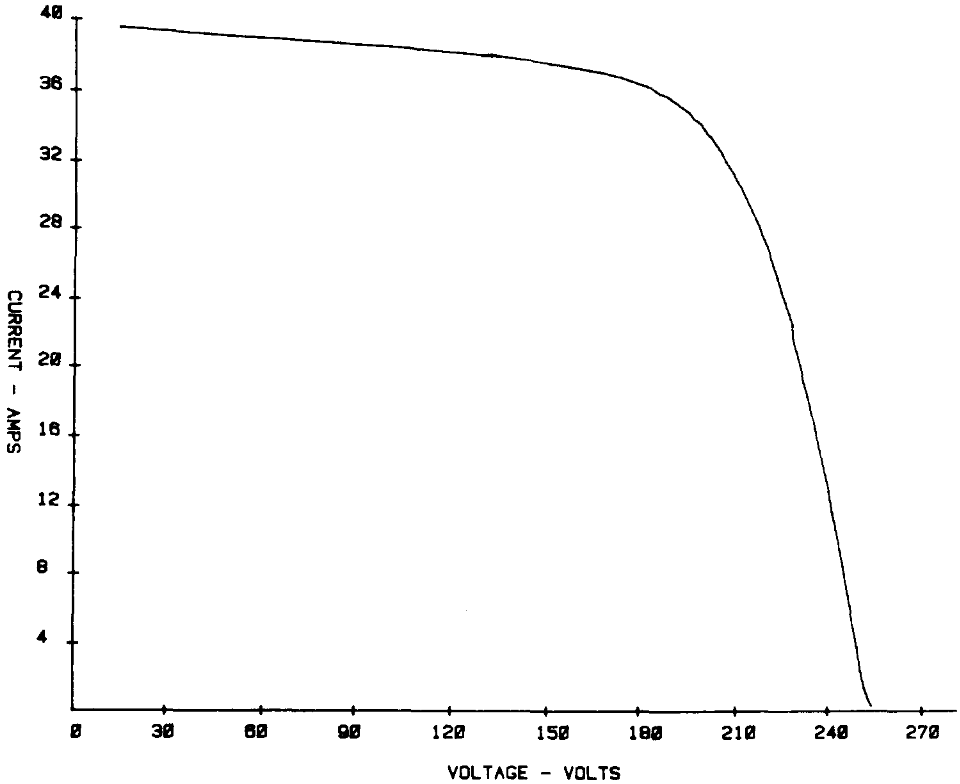

Fig. 5. *I–V* curve of a 7.5 kW_p array (ambient temperature, 16.5 °C; cell temperature, 54.0 °C; insolation, 94.6 mW cm^{-2}; V_{oc} = 255 V; I_{sc} = 40.0 A; P_{max} = 6880 W (196 V, 35.0 A)).

TABLE 1

Comparison of 10 kW instruments

	Resistive load	*Capacitive load*	*Hewlett–Packard 85 computer*
Weight (lb)	125	13	20
Size (ft^3)	4.3	0.5	1.08
A.c. power (W)	240	20	30
Cost (U.S. $)	11000	8000	4000

4. Conclusions

The capacitive load curve tracer offers many distinct advantages over resistive load boxes for making *I–V* curves. The required capacitors are available and are not very bulky. In fact, a 100 kW version of this device is now being assembled at Lincoln Laboratory and it is not substantially larger than its predecessor. Fast scanning techniques can be used on entire arrays to detect faults and large degradations.

Acknowledgments

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