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**PORTABLE ELECTRONIC LOAD
FOR FIELD MEASUREMENTS
OF PHOTOVOLTAIC SYSTEMS**



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PORTABLE ELECTRONIC LOAD FOR FIELD MEASUREMENTS OF PHOTOVOLTAIC SYSTEMS

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Summary:

A portable instrument consisting of an electronic load and a data acquisition system for measuring I-V curves of photovoltaic power plants with short circuit currents up to 80 A or open circuit voltages up to 500 V.

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1. SCOPE

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For a photovoltaic system, the I-V curve is the most important characteristic of its performance. The curve shows the current as a function of the voltage ($I=f(V)$)

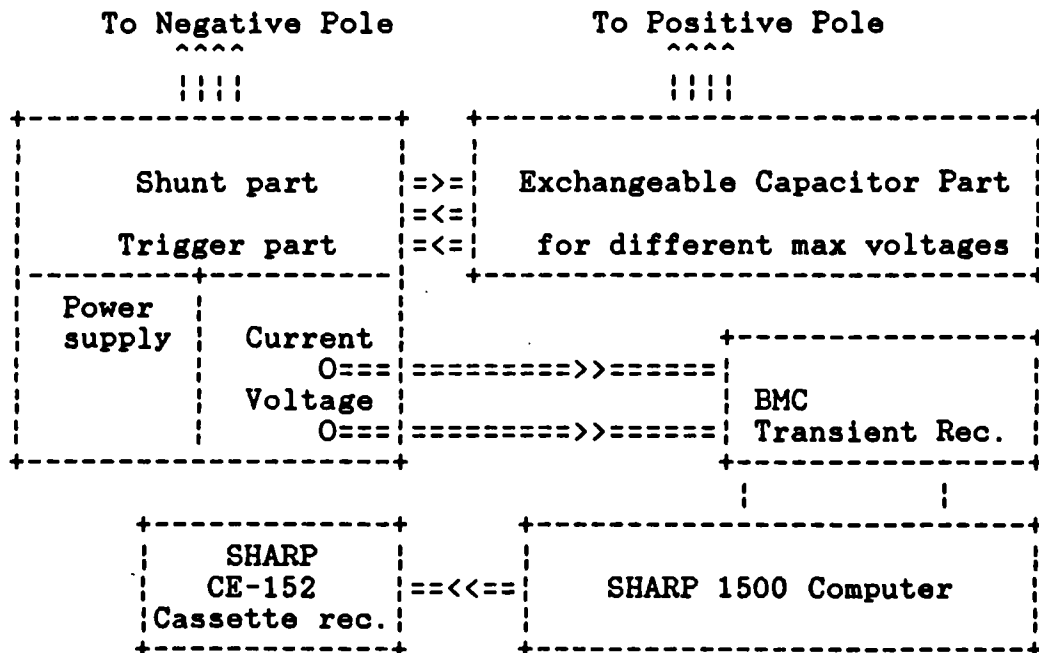
On this curve three points are of particular importance:

- 1) Short circuit point : where the voltage across the array (or module) is 0 and the current maximal
- 2) Maximum power point : where the product of current and voltage has its maximum.
- 3) Open circuit point : where the current is 0 and the voltage maximal.

With a variable resistor (from 0 Ohm to a very high value) one could sweep through the whole I-V curve, recording for each point current and voltage. This method is inconvenient due to the physical dimensions of such a resistor for portable measurements.

1.1 Description of the instrument

For portable measurements we developed a capacitor type electronic load connected to a BMC Transient Recorder and a Sharp 1500 Computer. The figure below gives a global view of the different parts of the instrument.



A simple diagram of the electronic load part, consisting of the capacitor and shunt part is given below

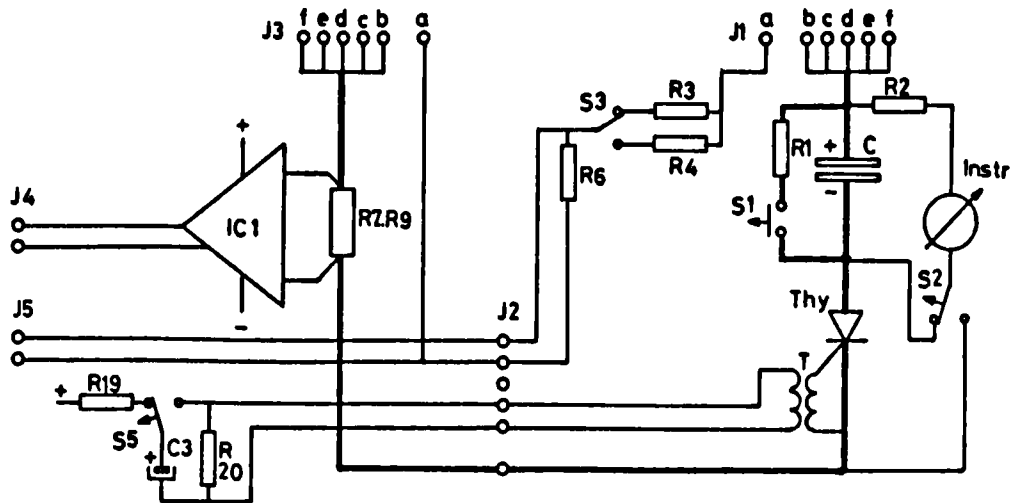


Figure 2: Diagram of the electronic load

The array under test is connected with the positive lead to the capacitor and with the negative to the shunt. Before starting a measurement the capacitor C should be discharged (voltage across the capacitor zero) which is done by pressing the discharge button S1. The discharge current is limited by the resistor R1. When the thyristor Thy has been triggered by a pulse from button S2, the capacitor starts charging until the current drops below the hold-current of the thyristor Thy. As the hold-current of the thyristor is about a few milliamperes the array under test reaches its Voc condition (open circuit point). During the charging time the current and array voltage are recorded by the BMC transient recorder. The same two channels (voltage and current) connected to a storage scope in the X-Y mode would also give an I-V curve. The accuracy of such an I-V curve depends on the storage scope used. The current is measured differential across the shunt, the array voltage is measured using a 4-wire connection to ensure that voltage drops due to wire resistance are not subtracted from the array voltage. The charging time of a given capacitor and Isc(short circuit current) can be estimated by the formula:

$$t = C * Voc / Isc$$

with:

| | |
|-----|-------|
| t | [s] |
| C | [F] |
| Voc | [V] |
| Isc | [A] |

In previous loads, we had in one enclosure different capacitors and shunts. They were selected for the different measurements by switches. Considering the high currents (up to 40 A) or high voltages (up to 500 V) we decided to eliminate these switching devices in the main loop. This means that only one fixed shunt and different capacitors in separate boxes with a high quality connection between the two parts, should be used. For safety reasons the following items should be included in each of these capacitor boxes:

- 1) Discharge resistor with press button
- 2) Visual indicator of the capacitor voltage
- 3) Thyristor with pulse transformer
- 4) Voltage output of only 5V for the data acquisition system

The choice of different capacitor boxes depends on the Voc to be measured, so no unnecessary weight has to be carried. The instrument also has two internal batteries for the shunt Opamp and trigger signal and supplies power for more than ten hours. However for the BMC transient recorder and the Sharp computer an external battery set is needed due to the higher power consumption.

2. INSTRUMENT DETAILS

=====

2.1 Capacitor parts:

The values of the working voltages of the electrolytic capacitors were chosen according to several years of acceptance test experience. The main working voltages were: 25; 85; 200; 250; 350; 500 V. After an in depth study of electrolytic capacitor vendors, Sprague was chosen because they had just announced a new range of hermetically sealed computer grade elco's. These are the elco type 88D which have dimensions of l= 41.2 b=41.2 h=30 mm. We received 6 capacitors with 4 different working voltages free of charge. The values of these samples are listed in table 1

| DC working voltage | DC surge voltage | Capacitance uF |
|-----------------------|---------------------|-------------------|
| 75 | 95 | 3300 |
| 250 | 300 | 470 |
| 360 | 400 | 220 |
| 450 | 525 | 150 |

Table 1: Values of Sprague 88D elco's

With these ranges of dc voltages I decided to make 4 separate capacitor parts (four Cboxes). The diagram of each Cbox is the same and only some component values are different. The diagram is shown in figure 3 and the components values are in table 2.

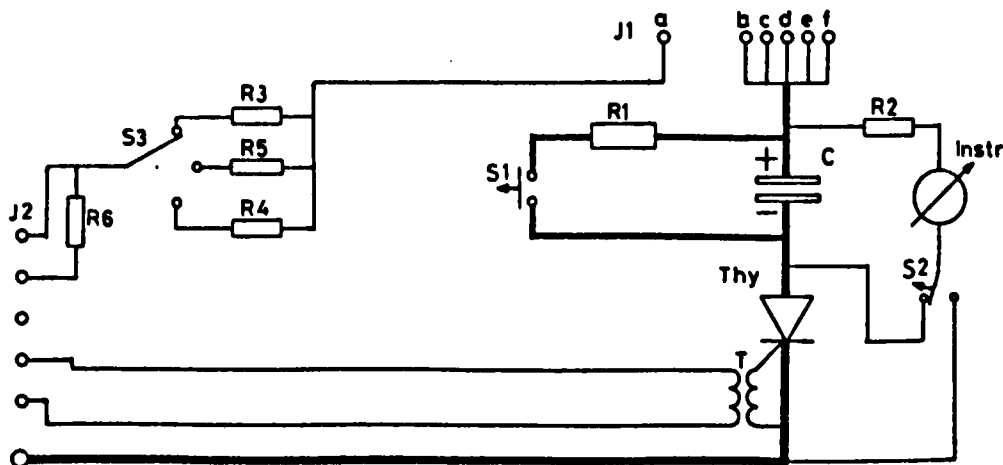


Figure 3: Diagram of the Cbox

| | Cbox 1 | Cbox 2 | Cbox 3 | Cbox 4 |
|---------|--|-------------|-------------|-------------|
| Voltage | 25 ; 85 | 200;230;275 | 320 ; 380 | 420 ; 500 |
| C [uF] | 19800 | 2820 | 1320 | 900 |
| Thy | 2N5446 | | | |
| R1 | 47 25W | 100 25W | 470 25W | 1 K 25W |
| R2 | 1.7 M 10% | 5.5 M 10% | 7.6 M 10% | 10 M 10% |
| R3 | 103.1 K .5% | 348.4 K .5% | 484.2 K .5% | 638.1 K .5% |
| R4 | 26.01K .5% | 290.1 K .5% | 406.8 K .5% | 535.3 K .5% |
| R5 | - | 251.1 K .5% | - | - |
| R6 | 6.19K .5% | 6.19K .5% | 6.19K .5% | 6.19K .5% |
| S1,S2 | Press button Contact rating 6A/250 Vac | | | |
| S3 | C&K 7201 | C&K 7411 | C&K 7201 | C&K 7201 |
| T | Pulse transformer Type: VAC 407/123- 01-PF 460 | | | |
| J1 | Amphenol MS3102E14S-6P | | | |
| J2 | Lemo Type MIH RA 3703 x 1 + 5 | | | |
| Instr. | 50 uA indicator (we used :SEW MR-38P) | | | |

Table 3: Component list for the different Cboxes

Each Cbox was made of two plastic boxes mounted together and forming a compact block. Inside the lower part of this box the six capacitors were soldered close together with copper strips in order to reduce the inductance.

The thyristor and pulse transformer are mounted directly on the negative strip, and the discharge resistor above one of the strips. The connectors, switches, instrument and divider-resistors (R3 .. R6) were mounted in the upper part.

The physical dimensions of each Cboxe are including connectors, are: l=150, b= 75, h= 100 mm

2.2 Power supply and shunt part

The power supply (Type Delta Electronica +-15V/100 mA) is used for the Opamp, for the trigger circuit and for charging the two 9V/100 mAh NiCd batteries. In case of normal mains connection these two batteries were kept at 9.8 V (The power supply is adjusted for that value). If no mains power is available, these two batteries will power the load for more then 10 hours.

Normally this time is more than sufficient because reliable measurement can only be done with solar irradiation of more then 600 W/m², i.e. normally not before 10 am and not after 4 pm. As shown in figure 4 we used germanium transistors (2N1302) as diodes (collector and base connected together) because they give a lower voltage drop than normal Si diodes (0.4 vs 0.7 V).

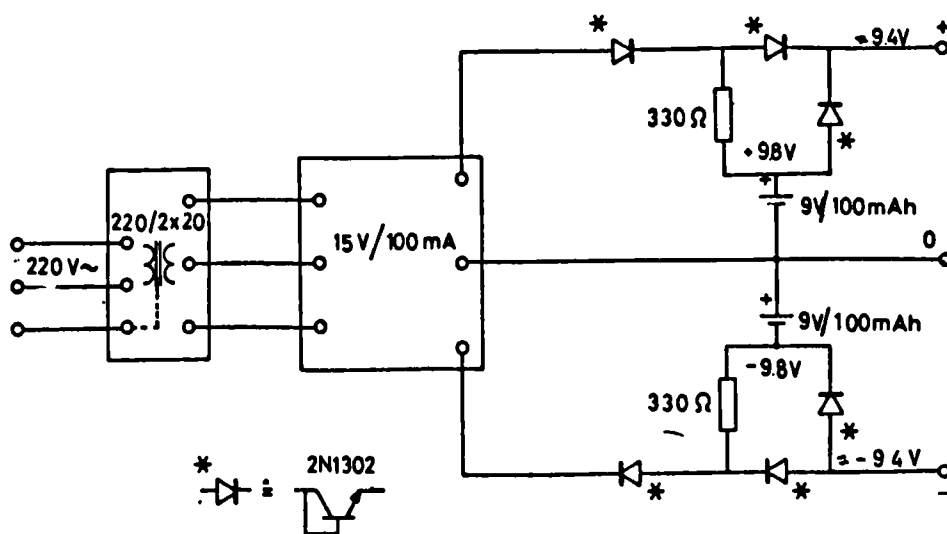


Figure 4: Diagram of the power supply

The shunt, Opamp and trigger circuit are mounted in the same plastic enclosure. Because of the low resolution of our A/D converter (8 Bits) we needed more than one range for the current measurement. The lower range should be around 3A and the higher range around 50A. So we made a compromise for the middle range of 12 A. The Opamp is a precision instrumentation amplifier type AD 624CD from Analog Devices.

Considering the currents mentioned above, the possible gains of the AD 624, and the precision shunt resistors in stock; the value of the shunt became 3.33 mOhm (3 resistors of 10 mOhm parallel). With this shunt on the three current ranges we could use two pin programmable gains: gain 500 for the 3A range and gain 125 for the 12A range. For the 48A range a resistor of 1.378 KOhm was needed.

The exact value of this resistor is not so critical because for each range the conversion factor between current and output voltage (to A/D converter) is used for further data handling. The determination of these factors is described in chapter 3 (Calibration procedures). The diagram of the shunt part is given in figure 5. The table of used material is table 4.

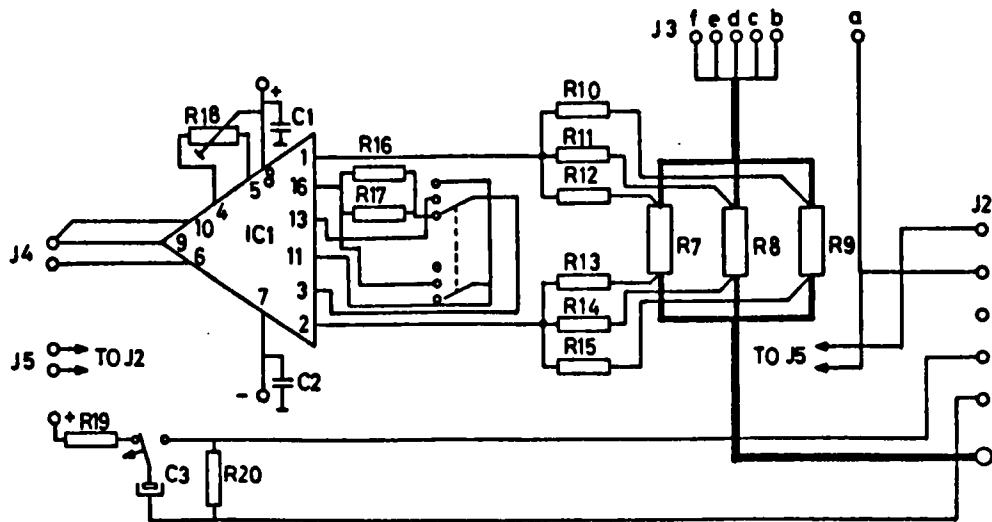


Figure 5: Diagram of the shunt part.

| | | | |
|----------|--------------|---------------------|------------|
| IC1 | AD 624CD | Analog Devices | |
| R7..R9 | .01 Ohm 1% | Dale RH-10 | 10W |
| R10..R15 | 100 Ohm 1% | | |
| R16 | 2.0 KOhm 1% | | |
| R17 | 3.9 KOhm 1% | | |
| R18 | 10 KOhm | 10 turns trimpot | |
| R19 | 5.6 KOhm | | |
| R20 | 100 Ohm | | |
| C1,C2 | 100 nF | Cer. cap | |
| C3 | 10 uF/ 63V | Elco | |
| S4 | C&K 7411 | | |
| S5 | Press button | Contact rating | 6A/250 Vac |
| J2 | Lemo | MIH RA 3703 x 1 + 5 | |
| J3 | Amphenol | MS3102E14S-6P | |
| J4,J5 | BNC | chassis isolated | |

Table 4: Component list for the shunt part

2.3 Data acquisition part

The data acquisition part consists of three items:

- 1) BMC transient recorder MC-12
 Manufacturer: BMC Dr.Schetter
 Nordenstr.34
 D-8039 Puchheim/Muechen
 Germany
- 2) Sharp PC-1500A computer
- 3) Sharp CE-152 portable cassette tape recorder

On the BMC transient recorder the first two channels are used. Each channel has an impedance of 1MOhm when the recorder is switched on (in the off state the impedance is 1KOhm). The recorder is used in unipolar mode and the input voltage should not exceed 4.94 Volt. The value of the irradiance could also be measured by the recorder, but we prefer to measure that separately and enter it manually into the program (see annexe 7.1 for program listing (line 190)). The recorder starts measuring after the current voltage reaches a certain level. We put this level on 1/32 of the full-scale input voltage (4.94 V). The scan time for recording a pair of voltage and current voltages is 50 us. For a normal I-V curve 30 data points are sufficient so the shortest measurement time is c. 1.5 ms.

While the time for a complete measurement depends on the value of the capacitance and the value of V_{oc}/I_{sc} (see formula on bottom page 4) the number of data points will not be constant. In table 5 the maximum currents are calculated with a scan time of 10ms at different V_{oc} .

| | V_{oc} [V] | C [mF] | I_{sc} [A] |
|--------|--------------|--------|--------------|
| Cbox 1 | 25;85 | 19.80 | 170 |
| Cbox 2 | 200;230;275 | 2.82 | 77 |
| Cbox 3 | 320;380 | 1.32 | 50 |
| Cbox 4 | 420;500 | 0.90 | 45 |

Table 5: Theoretical maximum values of I_{sc} which can be measured.

The capacitor should, except in the first case, withstand such currents because the maximum DC load current of each capacitor is 25A. In each Cbox there are 6 mounted in parallel so that would result in a maximum current of 150A!

Because the memory of the transient recorder can store up to 7000 measurement values we can store more data points than needed and average by software over 2 or 4 data points, in effect increasing the accuracy.

When the scan is finished the recorder stops recording and the data points are read into the Sharp 1500A computer via its system bus. Then the computer continues its memory resident program, asks for irradiation value and measurement ID and plots the curve in a normalised form on the plotter. If a tape recorder is used, the data can also be written on tape.

Later we can reread these data into the Sharp 1500A computer and send it via RS232 to any other computer for further elaboration or data backup. The tape recorder is not really necessary because the plots of the Sharp 1500A are good enough to be digitised them for further elaboration.

2.4 Connection between different parts

Before discussing the connections we must realise that we are working with high DC currents and voltages. Connectors with these specifications are hard to find, expensive or too big and heavy. The connectors which we used were not specified for these high currents but we are working with peak currents for very short times.

The connectors from the capacitor part to the array, and from the shunt part to the array were already there and worked fine. The only connection which was new was that between capacitor and shunt part.

I chose the LEMO connector because it has several poles, solid construction and, most importantly, it plugs only in one way (this connector is also used for the array voltage sense directly to the computer). The connection between the two parts is c. 7 cm long and has two LEMO F 3703 x 1 + 5 connectors. The main current wire is 2.5 mm^2 , the other 5 wires 0.75 mm^2 (2 wires for pulse transformer, 2 wires for voltage sense and one spare). The in house made cable is covered with a metal shield for two reasons: both connectors have same potential and better mechanical properties. The connection between shunt part and BMC transient recorder consists of two BNC cables. The cables for connecting the load to the array under test are each 2 m long, $3 * 2.5 \text{ mm}^2$ (2 wires for current, 1 for voltage sense). On one side an Amphenol MS3106E14S-6S (connection to capacitor part or shunt part) on the other side a block connector to which we can connect adaptor cables for the different installations.

The power connection to the Sharp 1500A computer, BMC transient recorder and cassette recorder are made by factory delivered 9V power supply units. In case we have no mains supply we connect a 12V/9.5 Ah accumulator to the Sharp/BMC and a 6V/ 6 Ah to the cassette recorder.

3. CALIBRATION PROCEDURES

=====

For this load we claim an accuracy of 1% over the whole temperature range so we must calibrate this load under laboratory conditions with sophisticated calibration instruments. The instruments we use for calibration are:

- 1) 2701C programmable precision DC voltage standard
- 2) 4300B digital micro ohmmeter
both from Valhalla Scientific San Diego, Ca U.S.A.
- 3) Keithley 177 DVM
- 4) Shunt 10.0 mOhm .1%

The accuracy of these instruments is much better than the accuracy of the resistors we used so the final accuracy will be of the order of 0.5% for the voltage output and 2% for array current.

3.1 Array voltage

Connect a calibrated voltage between both voltage sense pins on the connectors J1 (pin A).

Measure the output voltage on BNC connector J3. The multiplication factor (V_{input} / V_{output}) is then noted and used in the software program. This measurement should be done for each voltage range.

3.2 Array current

This calibration measurement takes longer because it is done dynamically. The load is connected to a solar-panel or array and a precision (10 mOhm) shunt is installed in the negative lead. The voltage at J4 (from AD 624) and the voltage from the 10 mOhm calibration shunt are measured with the BMC transient recorder. The value of the current amplified by the AD 624 and elaborated by the program, and the value of the calibrated shunt must be equal. With one I-V curve the program recorded 62 currents values and with a few I-V curves you can calculate the conversion factor statistically reducing the tolerance from 2% to 1.5%. This measurement can be done with a minor change in the normal program.

3.3 BMC transient recorder

The calibration procedures for the BMC transient recorder are described in its manual. Briefly:

Connect a 4.942 voltage on the input of channel 1, load the multimeter program and adjust the trimpot on the recorder until the display of the Sharp 1500 computer shows alternating 4.942 V and Overflow.

4. OPERATING INSTRUCTIONS =====

With such instruments you are always working with live voltages; the connections to the array or module are not isolated. This means that you should always handle one connector at the time. Also, the capacitors when charged can deliver a dangerous current. So never open the box when the capacitors are loaded! Now to the instructions:

- 1) For a given measurement choose one of the four Cboxes and connect it with the appropriate cable to the shunt part. If 220 Vac is available connect the mains plugs to the shunt-power supply part and to the power supply unit of the BMC-Sharp combination and connect the two BNC cables from the current and voltage sense to channel 1 and 2 of the BMC transient recorder.
- 2) Start the program and enter the values for the parameters needed in the program.
- 3) Connect the negative lead to the negative connection of the module or array and then the positive lead to the positive connection. Be sure that the polarity is correct (test it with a voltmeter before)!
By pressing the array voltage switch on the Cbox (S2) you can control if the connections are well made.
- 5) If the irradiation of the sun is stable a first I-V curve can be measured and plotted. After the plot is ready you may have to change the values of the scantime and/or the value of AV (average).
- 6) Be sure that the upper part of the I-V curve is not clipped (too much current in I_{sc} so that the voltage increases above 4.94 V) and that during the scantime the array or module under test reaches V_{oc} . The first problem can be solved by selecting a higher current range and modifying the conversion value in the program (C1); the second one by changing the scantime (TT).
A voltage divider was made to add the full scale ranges of 6,24 and 96 A to the existing ranges of 3,12 and 48 A.
The voltage divider was made in a metal box with two BNC connectors and two .1% resistors.
After a satisfactory plot the data can be stored on a cassette recorder and if the V_{oc} at standard conditions is known, I_{sc} and P_{max} to extrapolated standard conditions can be calculated.
Before each measurement, or before changing the leads to an other array, the capacitor must be fully discharged. When the V_{oc} is at the limit of the capacitor DC surge voltage it is better to discharge the capacitor as soon the computer starts to plot.
When the irradiation is steady a measurement cycle takes about four minutes (changing leads, plotting and writing the data on tape).

5. HINTS FOR FUTURE IMPROVEMENTS

=====

If the instrument is not used for a long time the capacitors should be conditioned by a voltages of $.8 * \text{working voltage}$ for a few hours or even a whole night. This is to reduce the leakage current which may not exceed the hold current of the thyristor.

In the design described herein, the capacitor box should be opened for this task, and due to the compact mounting it is rather difficult. Perhaps an extra connector directly connected to the two poles of the capacitor would be useful this task but it is also dangerous. Another problem is the power consumption of the data acquisition part, Sharp computer when the plotter is used, and the cassette tape recorder. In the future, another two channel A/D converter card with on board memory and RS232 output could probably reduce the power consumption leading to lower weight of this portable instrument due to fewer, or no batteries at all.

6. LITERATURE

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 "On-site Acceptance Testing of Large Photovoltaic Arrays"
 proc. 5th European Photovoltaic Solar Energy Conference
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G. Blaesser, K.H. Krebs, H. Ossenbrink, E. Rossi
 "Acceptance Testing and Monitoring the CEC Photovoltaic Plants"
 proc. 6th European Photovoltaic Solar Energy Conference
 London (UK), April 1985, pg. 481

7 ANNEX
 =====

7.1 Program listing for Sharp PC-1500A computer

```

10 "A":REM DYNAMIC LOAD
20 WAIT:PRINT "NEW PARAMETERS?"
25 CLEAR
30 DIM I1(62),V1(62)
40 INPUT "CAL. C1,C2,C3:";C1,C2,C3
50 INPUT "RANGES R1,R2,R3:";R1,R2,R3
60 INPUT "AVERAGE(1,2,4):";AV
65 INPUT "SCANTIME ( us ):";TT
70 "S":INIT:REM INTERFACE INIT
75 INIT U
80 BUFINIT 2,2
90 SETRANGE 1,R1
100 SETRANGE 2,R2
110 SETRANGE 3,R3
120 SETTRIGGER R1/32
130 SETSCANTIME TT*1.0E-6
140 SELECT +1,1;2,2
150 WAIT:PRINT "READY FOR SCAN"
160 REM START OF IV-SCAN
170 INSCAN
180 IA=C3*CHA(3)
190 INPUT "IRRADIANCE <W/M^2>:";VA
194 IA=C3*VA
200 FOR I=1 TO 62
210 IS=0:VS=0
220 FOR J=1 TO AV
230 BUFREAD 1,AV*(I-1)+J,K
240 IS=IS+K
250 BUFREAD 2,AV*(I-1)+J,K
260 VS=VS+K
270 NEXT J
280 I1(I)=C1*IS/AV:V1=C2*VS/AV
290 NEXT I
300 PRINT "READY FOR PLOT"
310 IO=I1(1)
320 VO=V1(62)
330 INPUT "MEAS-ID:";A$
340 LPRINT "ID=";A$:LPRINT "TIME=";TIME
350 LPRINT "*MEASURED DATA *":LF 10
360 GRAPH :COLOR 1
370 GLCURSOR (50,0):SORGN :GLCURSOR (0,160)
380 FOR I=1 TO 62
390 I2=I1(I)/IO:V2=V1(I)/VO
400 LINE -(V2*160,I2*160)
401 LINE -(V2*160+2,I2*160+2)
402 LINE -(V2*160-2,I2*160-2)
403 LINE -(V2*160,I2*160)
410 NEXT I
420 LINE (0,0)-(160,160),0,3,B
430 FOR I=1 TO 4
440 LINE (32*I,0)-(32*I,160),0,3

```

```

450 LINE (0,32*I)-(160,32*I),0,3
460 NEXT I
470 CLCURSOR (-40,180):LPRINT "I/Isc"
480 CLCURSOR (110,-30):LPRINT "V/Voc"
490 TEXT :LF 2
500 PM=0:IM=0:COLOR=0
510 FOR I=1 TO 62
520 IF I1(I)*V1(I)<PM GOTO 550
530 PM=I1(I)*V1(I)
540 IM=I
550 NEXT I
560 USING #####.###"
570 LPRINT "Isc=";I0
580 LPRINT "Voc=";V0
590 LPRINT "Vmp=";V1(IM)
600 LPRINT "FF=";PM/I0/V0
610 LPRINT "IA=";IA
620 LF 2:LPRINT "CALIBRATIONS:"
630 LPRINT "C1=";C1
640 LPRINT "C2=";C2
650 LPRINT "C3=";C3
660 USING :LF 2
670 PRINT :TAPE READY?"
680 PRINT #A$;TI,C1,C2,C3,IA,I1(*),V1(*)
690 INPUT "Voc-stc=";VR
700 IM=0:PM=0:DV=VR-V0
710 FOR I=1 TO 62
720 P=I1(I)*(V1(I)+DV)
730 IF P<PM THEN GOTO 750
740 PM=P:IM=I
750 NEXT I
760 LPRINT "EXTRAPOLATED DATA"
770 USING #####.###"
780 LPRINT "Isc-stc=";I0*1000/IA
790 LPRINT "Voc-stc=";VR
800 LPRINT "Pmax-stc=";PM*1000/IA
810 USING :LF 4:STOP
820 "D":REM READ TAPE AND SEND TO RS232
830 SETCOM 1200
831 SETCOM 1200:OUTSTAT 0:SETDER PO
832 FOR I=1 TO 62
833 V1(I)=999
834 I1(I)=999
835 NEXT I
840 INPUT "FILE-ID=";A$
851 INPUT #A$;TI,C1,C2,C3,IA,I1(*),V1(*)
855 USING #####.###"
860 LPRINT A$,TI
865 USING #####.###"
870 LPRINT C1;C2;C3
880 LPRINT IA
890 FOR I=1 TO 62
900 LPRINT V1(I),I(1)
910 NEXT I
920 STOP

```



