UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.704 - 6

Workshop on Materials Science and Physics of Non-Conventional Energy Sources

(30 August - 17 September 1993)

"On-Site Measurement of the Performance of PV Arrays"

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These are preliminary lecture notes, intended only for distribution to participants.

ON-SITE MEASUREMENT OF THE PERFORMANCE OF PV ARRAYS

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1. INTRODUCTION

When a PV array has been installed, the purchaser or responsible authority sometimes requires an on-site measurement of its performance, in order to confirm that the rated power complies with the specification. In the case of large pilot or demonstration projects, the measurement may be repeated after a period of time, to detect any degradation.

The measurement consists of tracing the current-voltage characteristic of the array and transposing the resulting curve to Standard Test Conditions. The rated power is then read off. If the array is too large to measure as a whole, parts of it are measured in turn and the total power determined from these data.

On-site measurements present a number of problems :-

1) With a fixed tilt array, the solar beam is seldom at normal incidence to the modules, so a minimum irradiance of 800 W/m^2, as specified in IEC 904-1 for module rating in natural sunlight, may prove difficult to obtain.

2) The irradiance in the plane of the modules is not always uniform over the whole array field.

3) It is not always possible to achieve the accuracy of $\pm$ 0.5% specified for voltage and current measurements in IEC 904-1. Some relaxation is therefore necessary.

4) For the purpose of transposing the measured characteristic to STC, it is necessary to know the cell junction temperature. This can vary considerably over the array.

The CEC Joint Research Centre, Ispra has long experience in this area of solar technology and they have helped the IEC to tackle these problems in preparing an international standard for on-site array measurements. The procedure described in this lecture is based on the latest draft to emerge from this collaboration. Experience has shown that, if it is followed, an overall accuracy within $\pm$ 5% can usually be achieved.

2. EQUIPMENT

The following equipment is required (Fig.1) :-

1) A PV reference device that has been selected and calibrated in accordance with IEC 904-2. Preferably, it should be encapsulated in the same way as the modules in the array, so that it reaches the same steady-state temperature.

2) A bracket for mounting the reference device co-planar with a module in the array or subarray under test. The misalignment error should be less than $\pm$2%.

3) A precision resistor for measuring the short-circuit current of the reference device.

4) 2 portable radiometers for checking the uniformity of the in-plane irradiance. (Not necessary for small arrays).

5) Voltage and current measuring instruments complying with IEC 904-1, except that the accuracy shall be within ± 1%.

6) Means for measuring the ambient temperature to within ± 1°C.

7) A variable load suited to the power range of the array or subarray under test. A capacitive load, as developed by JRC and other agencies, is recommended.

8) An X-Y plotter or digital storage oscilloscope for tracing the I-V curve.

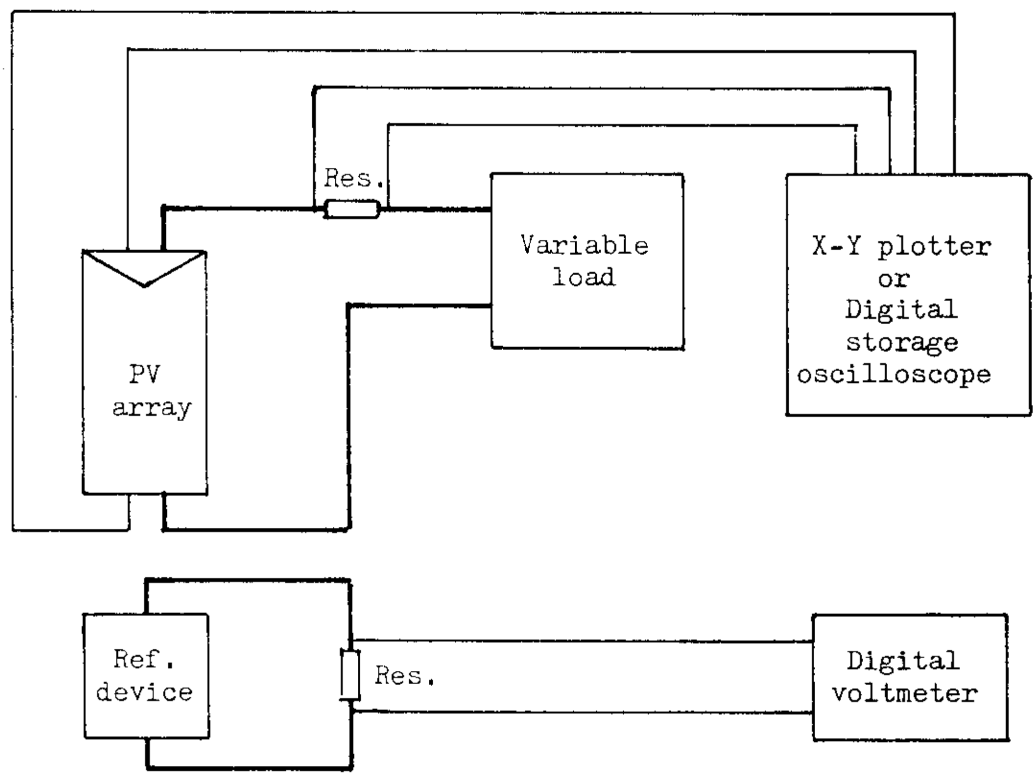

Fig.1 TEST CONNECTIONS

3. WEATHER CONDITIONS

Measurements should be made only on sunny days under the following conditions :-

- Average in-plane irradiance not less than 600 W/m^2.
- Irradiance fluctuations in the course of a measurement not to exceed ± 1%.

4. PROCEDURE

1) Ensure that the windows of all modules are clean. If this is not practicable, an estimate of any power loss due to soiling should be made from tests on comparable groups of cleaned and uncleaned modules and this loss applied as a correction to the measured data.

2) Using one of the portable radiometers, check the uniformity of the in-plane irradiance over the array or subarray to be measured (hereafter referred to as the "test specimen"). Keep the second radiometer stationary to monitor any temporal fluctuations and correct the readings of the moveable radiometer as necessary. (This step may be omitted for small arrays).

3) Select a module on which the irradiance has a mean value and mount the reference device on this module, using the bracket.

4) Disconnect the test specimen at the subarray paralleling board or other convenient point and connect it to the test circuit. Connect the reference device to its instrumentation. (Fig.1)

5) During the day, make repeated simultaneous readings of :-

V_{OC} , the open-circuit voltage of the test specimen (V),

T_A , the ambient temperature (^oC) and

G_I , the in-plane irradiance, as determined by the reference device (W/m^2).

These measurements should be taken over as wide a range of irradiances as possible.

6) From each set of data, compute the open-circuit voltage of the test specimen at STC, thus :-

$$V_{OC,STC} = V_{OC} + N_S \left[V_T . \ln(1000/G_I) + \beta \left\{ \frac{dT_J}{dG_I} . G_I + T_A - 25 \right\} \right]$$

where : N_S is the number of modules in series in the test specimen

V_T is the diode thermal voltage of the module (ca. 0.025V/cell)

β is the temperature coefficient of voltage of the mc (ca. 0.0022V/^oC per cell)

$\frac{dT_J}{dG_I}$ is the slope of the graph relating the equivalent cell temperature of the array T_J to the irradiance G_I. For free-standing arrays with a NOCT of 45^oC, this term may be assumed to be 0.03$^oC/(W/m^2)$.

7) Calculate the average $V_{OC,STC}$ from the values derived from the individual measurements.

8) Trace the I-V characteristic of the test specimen and, at the same time, note the short-circuit current of the reference device. The scan time should be between 20 and 100ms and the number of points on the I-V curve should be at least 50.

9) Transpose the current and voltage at each point on the measured I-V characteristic to STC, as follows :-

$$I_2 = I_1(1000/G_I)$$

$$V_2 = V_1 + (V_{OC,STC} - V_{OC}) - R_S(I_2 - I_1)$$

where : I_1 and V_1 are the current and voltage co-ordinates at a point on the measured characteristic

I_2 and V_2 are the co-ordinates of the corresponding point on the transposed characteristic at STC

$V_{OC,STC}$ is the average value determined in Step 7

V_{OC} is the open-circuit voltage of the test specimen, as determined during the scan.

R_S is the series resistance of the test specimen and associated cabling.

Note The above transposition equations are simpler than those specified in IEC 891 for the transposition of module characteristics. (See Appendix for these equations). The main differences are :

- Currents are transposed by simply multiplying by the ratio of the standard irradiance ($1000W/m^2$) to the measured irradiance, G_I. There is no correction for temperature, as it is assumed that the reference device is at the same temperature as the modules.

- In the voltage equation, the term $(V_{OC,STC} - V_{OC})$ takes the place of $\beta(T_2 - T_1)$, thus overcoming the problem of measuring T_1, the array junction temperature. There is no curve correction term, as this has been found to be unnecessary.

R_S is determined by measuring the I-V characteristic of the test specimen at two different irradiances, say 600 and $1000W/m^2$. Both curves are then transposed to STC, using assumed values of R_S, until the value is found that results in the best match between the transposed curves. Once determined, the value of R_S may be assumed to hold good for other test specimens of the same configuration.

10) From the transposed characteristic, determine the maximum power and the rated power at STC.

11) If the array has been divided into sections for test purposes, repeat Steps 1 to 10 with the other sections.

12) Weather and time permitting, repeat the whole procedure on a different day.

13) Add the average values of the subarray rated powers to obtain the rated power of the complete array.

If the test specimen is disconnected for the measurement at the sub-array paralleling board, it must be realised that the measured data will include diode, module mismatch and cable losses. If it is desired to use the on-site measurement to calculate the total output power of the modules and deduce therefrom the mean module power for comparison with the maker's rating, an estimate of these losses must be made and added to the measured power.

APPENDIX

TRANSPOSITION EQUATIONS FOR MODULE I-V CHARACTERISTICS

(From IEC 891)

The measured current-voltage characteristic shall be corrected to Standard Test Conditions or other selected temperature and irradiance values by applying the following equations :

$$I_2 = I_1 + I_{SC}(I_{SR}/I_{MR} - 1) + \alpha(T_2 - T_1)$$

$$V_2 = V_1 - R_S(I_2 - I_1) - KI_2(T_2 - T_1) + \beta(T_2 - T_1)$$

where :

I_1 and V_1	are co-ordinates of points on the measured characteristic
I_2 and V_2	are co-ordinates of the corresponding points on the corrected characteristic
I_{SC}	is the measured short-circuit current of the test specimen
I_{MR}	is the measured short-circuit current of the reference device
I_{SR}	is the short-circuit current of the reference device at the standard or other desired irradiance
T_1	is the measured temperature of the test specimen
T_2	is the standard or other desired temperature
α and β	are the current and voltage temperature coefficients of the test specimen in the standard or other desired irradiance and within the temperature range of interest (β is negative)
R_S	is the internal series resistance of the test specimen
K	is a curve correction factor.