Short flash and constant load PV-module tester

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Abstract—**A measurement scheme is presented for obtaining the physical parameters of a photovoltaic module with a short light flash. The module is under constant load and voltage and current are recorded during the decaying illumination intensity of the flash. The physical parameters are extracted by means of the one diode model including voltage dependent capacitance. From these parameters the stationary current-voltage curve is reconstructed for a wide range of illumination levels.**

Keywords—characterization; photovoltaic module; flash test; capacitance; current-voltage curve

I. INTRODUCTION

In order to rate photovoltaic modules (PV-modules) their physical and electrical properties must be characterized. Usually this is done by measuring the current-voltage curve (I-V curve) under stationary or quasi stationary conditions (for characteristics of such systems, see, e.g. [1]). The latter method employs a flash light whose intensity is kept constant during recording of the I-V curve. Most commercial systems employ this method, because the pulse duration of the illumination of the photovoltaic module is sufficiently short to have virtually no heating of the module during the measurement. At the same time it is sufficiently long to render the influence of transient effects, as might be caused by the module's capacitance, negligible.

However, such commercial systems are relatively expensive due to the complex electronic circuitry which controls the rectangular intensity pulse of the flash lamp. In addition, they measure the I-V curve only at one or a few discrete light intensities, although in practice one is interested in the whole range of intensities to which the module will be exposed. But there have always been proposals for other methods of measuring the characteristics of PV-modules (e.g. [2]-[5]). One interesting method has been introduced in [4], although adapted to concentrator solar cells. The solar cell is kept at a certain voltage during the short flash time of a very cheap disco flasher. The constant voltage serves to reduce transient effects. The cell's current is recorded over the full range of illumination levels generated by the flash. While for a given intensity only one point of the I-V curve is obtained, measurements taken at various bias voltages permit to reconstruct the I-V curves for any light intensity covered by the pulse.

It would be interesting to be able to use the continuous range of intensities of a short pulse as used in [4] and [5], especially the exponentially dropping tail, and obtain from just a single pulse all the information for the I-V curves of stationary operation for any level of illumination. This should be possible, because a solar cell, or a whole PV-module, is an electronic device whose functioning principles are well known. Therefore, once its relevant physical parameters have been obtained in whatever method of measurement, its performance should be predictable under any operation conditions. For time dependent measurements this means that also the capacitance and its dependence on the momentary operating conditions have to be obtained from the data of the flash pulse. (In principle, also the inductance must be considered, but it is usually negligible.)

Here we present the test results of such a measurement scheme. It is similar to the schemes of [4] and [5]. But the concept is to use a suitably chosen *constant ohmic* load during the pulse and measure the voltage and the current of the PV-module as a function of the exponentially decaying illumination intensity. If needed, additional measurements with different ohmic loads can be made. In the following sections we first explain the experimental setup and then discuss the theoretical model and the procedure of parameter extraction.

II. EXPERIMENTAL

A. Experimental setup

The experimental setup is shown in Fig.1. A strobe light FL (Quantum Qflash X) is mounted 450 cm above the PV-module under test. Since this distance is not large enough to ensure a homogeneity of illumination of better than 2% by the $1/r^2$-law over the measurement area of 1 m x 2 m, patches of white reflective material were placed in the lower parts of the side walls of the setup until the desired homogeneity was reached. The intensity of the flash is measured by means of the fast photodiode PD (BPX61 by Osram), which is essentially a mono crystalline silicon solar cell of about 3 x 3 mm^2 area. The photodiode is under reverse bias from a 9 V battery. The current induced by the flash light is measured as the voltage over the noninductive 1 kΩ resistor R_M, which has low thermal drift. This voltage is fed into channel 1 of the oscilloscope OSC. The steep rise of this voltage when the strobe is flashed acts as the trigger for recording the signals. The PV-module under test deposits its output into a non-inductive ohmic load. Eight different loads can be chosen by the computer controlled switch S. In addition, there is a common resistor R_c of 0.47 Ω, which is also noninductive, and which serves for the measurement of the current. The total

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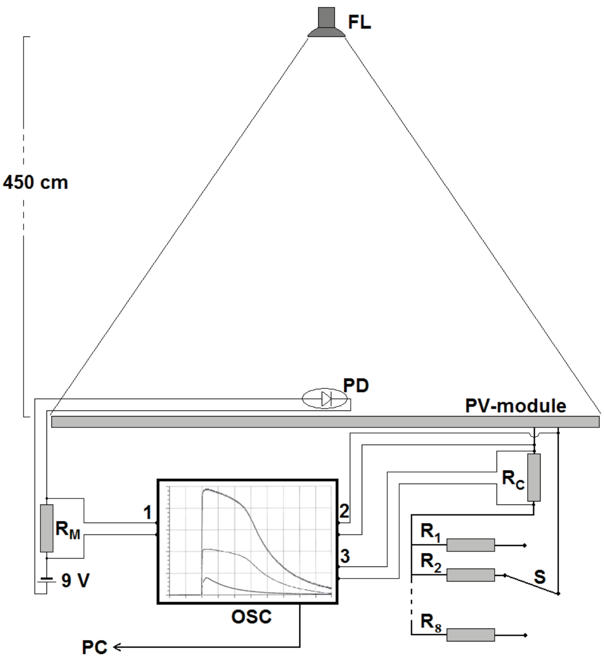

Fig. 1. Measurement scheme of the flash tester.

load R_T is thus comprised of the chosen resistor R_L (L = 1 to 8), the common resistor R_c, the contact resistance of the switch and the resistance of the cables to the two points at the PV-module, where the power is extracted. The voltage at these points is fed into channel 2 of the oscilloscope. Finally, the voltage across R_c is fed into channel 3 of the oscilloscope. The value of R_c is known with high accuracy so that the current of the module can be obtained from the data of channel 3.

B. Measurement data

A typical recording of a flash is shown in Fig.2. It was taken from a PV-module which had a maximum power of approximately 220 W under standard test conditions (STC). The module consisted of 82 series connected polycrystalline silicon solar cells of size 175.5 cm². The measurement was done at a temperature of 21°C. The signal from the photodiode (curve b) is proportional to the instantaneous light intensity. The decay from the maximum intensity to about 50% of the maximum occurs within 1.4 ms, and from the maximum intensity to about 10% of the maximum within 5 ms. About 5.2 ms after the trigger the intensity of the strobe light drops quite abruptly. These data are later discarded. The voltage of the PV-module (curve a) shows a slow decay at high intensities because with the chosen R_L the module happened to operate close to the open circuit condition at this illumination level, while for low intensities it operated closer to the short circuit condition. The bend from one part of the curve to the other occurs at the intensity where the PV-module goes through the maximum power point with the given total load, which occurs approximately at 2.2 ms.

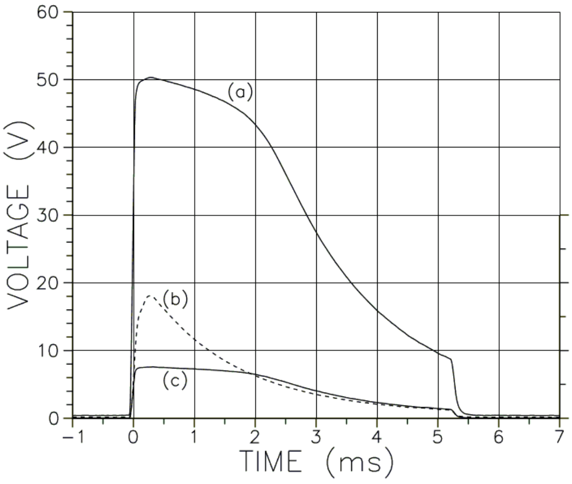

Fig. 2. Recording of one flash with a total load of $R_T = 15.673\ \Omega$ ($R_c = 0{,}47\ \Omega$). (a) Voltage of the PV-module, left vertical scale. (b) Voltage of the photodiode, right vertical scale. (c) Voltage across R_c, right vertical scale.

III. THEORETICAL BASIS

We will use the one diode model for the description of the PV-module. While for single cells a two diode model is more accurate [6], the series connection of a number of slightly differing solar cells in a PV-module justifies the one diode model with the ideality factor n as a free parameter. Since we have a time dependent illumination intensity H, we must also include the capacitance [6]-[8]. At time t the relation between current, voltage and illumination intensity can then be written as

$$I(V) = c_f H - I_0[\exp(qV_{\mathrm{int}}/(nkT)) - 1] - V_{\mathrm{int}}/R_p - C(V_{\mathrm{int}},\tau)\mathrm{d}V_{\mathrm{int}}/\mathrm{d}t. \quad (1)$$

The junction voltage is $V_{\mathrm{int}}=V+IR_s$. It is higher than the measured voltage V due to the internal series resistance R_s. For constant illumination the time derivative of the voltage vanishes and with it the influence of the capacitance so that the stationary form of the functional relation of the I-V curve is recovered. The capacitance C consists of the junction capacitance C_j and of the diffusion capacitance C_d [6]:

$$C(V_{\mathrm{int}},\tau) = C_j + C_d = C_{j0}/(1-V_{\mathrm{int}}/V_{\mathrm{bi}})^{1/2} + $$
$$+ [q\tau/(2nkT)]\, I_0\exp[qV_{\mathrm{int}}/(nkT)]. \quad (2)$$

Aside from the voltage dependence, which is also valid in the dark [7], an explicit dependence of the capacitance on the illumination level might be considered [8],[9]. We did not include this effect here, because it is relatively small [10], and in our measurement scheme it would be disguised as a further increase of capacitance with voltage. In principle one could also consider a dependence of the series resistance on the illumination level [11], but this effect is much smaller than that of the capacitance and was neglected here. The variables in (1) and (2) can be grouped into measured data on the one hand, and into parameters to be obtained from the data on the other. The data are:

I...current of the PV-module at time t

V...voltage of the PV-module at t

H...intensity of illumination at t

T...temperature of the PV-module

(k is the Boltzmann constant, q is the unit charge).

The parameters to be obtained from the data are:

c_f...conversion factor from intensity to photo current

I_0...saturation current

R_s...series resistance

n...ideality factor

R_p...parallel or shunt resistance

C_{j0}...junction capacitance at zero internal voltage

τ...lifetime of the minority carriers (of the base of the cell).

The built in voltage V_{bi} has to be supplied beforehand as it depends on the doping levels of the semiconductor. However, an approximate value of V_{bi} is sufficient, because the overall influence of the capacitances is not dominant with the given time constant of the decaying flash pulse.

In the following we will analyze two ways of extracting the physical parameters form the data $V(t)$, $I(t)$, $H(t)$. In the *quasi stationary* approach we will assume that the capacitance can be neglected, while in the *dynamical* approach we will take full account of it. From the difference of the extracted parameters we can draw conclusions how important the influence of the capacitance is, and whether it really needs to be considered when determining the practical quantities of interest, which, for a given level of intensity are the maximum power, the current and voltage at maximum power, the short circuit current and the open circuit voltage.

A. Quasi Stationary Analysis

Without the effects of the capacitance time can be ignored and the data from a flash can be seen as recordings of current and voltage as a function of illumination intensity. The time average of $V(t)/I(t)$ can be defined as the effective total load R_T. Using (1), the relation between illumination intensity and voltage becomes

$$c_f H = I_0\{\exp[qV(1+R_s/R_T)/(nkT)] - 1\} + V(R_T+R_s+R_p)/(R_T R_p). \quad (3)$$

The least-squares fit minimizes

$$\sum_i [H(V_{meas,i}) - H_{meas,i}]^2 \rightarrow min. \quad (4)$$

by varying the physical parameters c_f, I_0, R_s, R_p and n. $V_{meas,i}$ and $H_{meas,i}$ are the measured values of voltage and intensity, respectively, and $H(V_{meas,i})$ is the theoretical function (3) evaluated at the voltage $V_{meas,i}$. The summation goes over all measured points of the decaying tail of a flash, which were determined by the resolution of the oscilloscope (128 values over the chosen range of intensity). Fig.3 shows the data and the theoretical curve of four flashes with different loads R_L. The least-squares fit was done simultaneously to all four data sets. The different loads R_L were chosen such that good constraints on the fit parameters could be obtained. One notes the apparently very good agreement between measured and theoretical values despite the fact that time dependent capacitive effects were ignored. Since curve (a) was taken with a very large R_L, its data are close to the open circuit condition for all intensity values except below an illumination around 300 W/m². (Voltages above 50 V were discarded due to the oscilloscope's cutoff around 52 V at the chosen operating range. For similar reasons data at intensities below 230 W/m² were not included in the fit.)

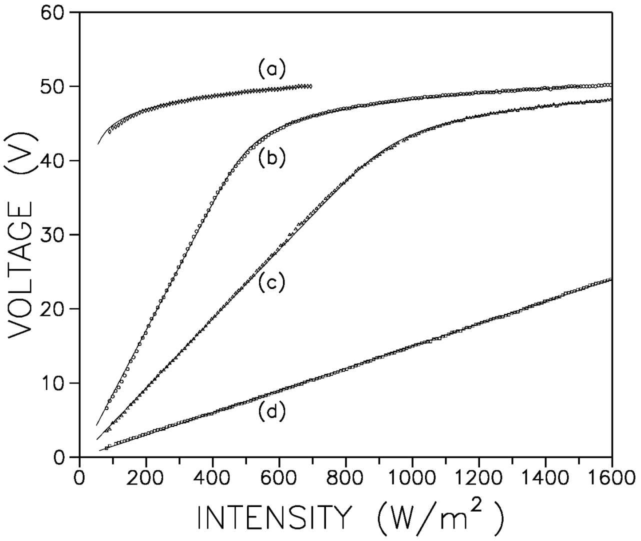

Fig. 3. Raw data of voltage at PV-module as a function of illumination intensity and results of least-squares fits according to (3) and (4). Raw data: Four flashes with different load resistances. (a) (diamonds) R_T=576.7 Ω; (b) (circles) R_T=15.67 Ω; (c) (triangles) R_T=8.350 Ω; (d) (squares) R_T=2.639 Ω. Fit curves: Full lines.

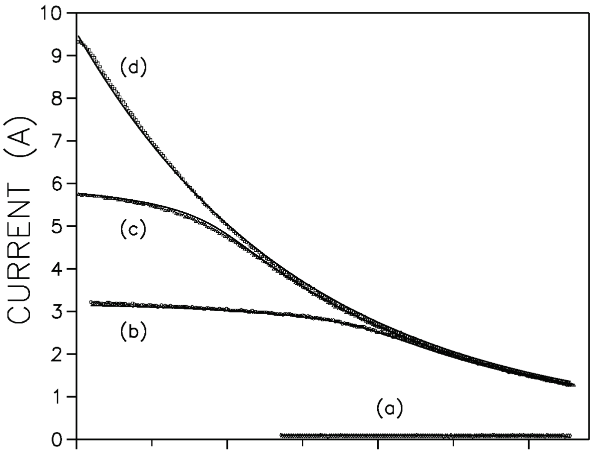

Fig. 4. Raw data of current of the PV-module from four flashes with the same four loads and shown with the same symbols as in Fig.3. The full lines are the fit curves from the dynamic analysis.

B. *Dynamic Analysis*

In the dynamic analysis the least-squares fit minimized the quadratic difference between the measured current at time t_i, $I_{meas,i}$, and the theoretically expected current as given in (1), thus

$$\sum_i\{I_{meas,i} - I[V(t_i)]\}^2 \rightarrow min. \qquad (5)$$

To reduce the noise of the data going into $I[V(t_i)]$, the derivative dV_{int}/dt (evaluated at t_i) and the voltage $V(t_i)$, were not taken directly from the data points, or the difference of the data points, respectively, but were smoothed with the help of their theoretically expected value using the parameters established in the quasi stationary fit. Similarly, $H(t_i)$ was not taken as the data point $H_{meas,i}$, but was obtained from the exponential fit to the decaying part of the illumination intensity. In this manner the theoretically expected current $I[V(t_i)]$ contained as much empirical data of the flash as possible, but was nevertheless a smooth theoretical function of time and all the fit parameters. Fig.4 shows the data and the fitted curves for the same four flashes as displayed in Fig.3. Again, one notes the very good agreement between measured data and theoretically expected values.

C. *Results of Quasi Stationary and Dynamic Analysis*

The parameters of the least-squares fits with and without the capacitance are shown in the upper half of Tab. I. For constant illumination of the PV-module only the parameters c_f, I_0, R_s, n and R_p are important, and from these the expected I-V curves for arbitrary illumination intensity can be reconstructed. The reconstruction of the I-V curves makes use of the stationary form of (1):

$$I(V) = c_f H - I_0\{\exp[q(V+IR_s)/(nkT)] - 1\} - (V+IR_s)/R_p. \qquad (6)$$

This equation can only be used for a reconstruction at the module temperature prevalent during the flash measurement. Transposition to other temperatures can be applied afterwards (e.g. [12]), but has not been done here. From the reconstructed I-V curves, one can then obtain the parameters of practical interest: The open circuit voltage V_{oc}, the short circuit current I_{sc}, the maximum power P_{max}, the associated voltage and current, $V@P_{max}$ and $I@P_{max}$, and the fill factor. The lower half of Tab. I shows the values of these parameters for an intensity of 1000 W/m² and a temperature as during measurement. Graphs of reconstructed I-V curves for illumination intensities of 1000 W/m² and 500 W/m², respectively, are shown in Fig. 5 (also for the temperature during measurement).

TABLE I.

Parameter	**Units**	**Value from quasi stationary analysis**	**Value from dynamic analysis**
c_f	A/(W/m²)	5.741	5.837
I_0	nA	0.5689	5.1509
R_s	mΩ	295.9	71.3
n	1	87.4	94.4
R_p	Ω	297.3	215.1
C_{j0}	µF	-	43.41
τ	µs	-	152.21
V_{oc}	V	50.9	49.8
I_{sc}	A	5.74	5.84
P_{max}	W	227.06	226.25
$V@P_{max}$	V	42.7	42.3
$I@P_{max}$	A	5.31	5.35
Fill factor	%	77.7	77.9

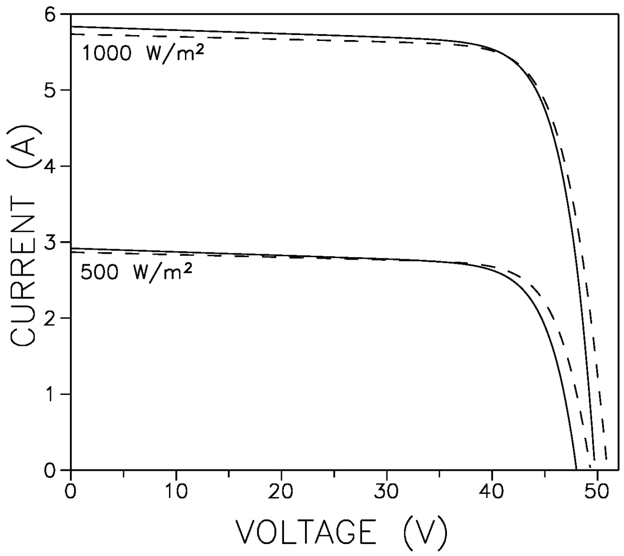

Fig. 5. Reconstruction of I-V curves for two different illumination intensities (500 W/m² and 1000 W/m²). Full lines: Dynamic analysis. Dashed lines: Quasi stationary analysis.

IV. DISCUSSION

As can be seen in Tab. I. and in Fig. 5, there is a general agreement between the quasi stationary and the dynamic analysis, but the expected differences are also noticeable. The dynamic analysis yields the more trustworthy results, because it includes the capacitances of the PV-module. When looking at the physical parameters, the saturation current I_0, the series resistance R_s and the ideality factor n all have a similar effect on the I-V curve in that they influence the open circuit voltage and the slope of the I-V curve between the maximum power point and the open circuit condition. These parameters are not linearly independent so that a change in one of them can be more or less compensated by changing the others to get almost the same I-V curve. Therefore their absolute values and the seemingly large differences between quasi stationary and dynamic analysis must be treated with caution. Still, in the voltage range from $V@P_{max}$ to V_{oc} the capacitance, and in particular the dynamic capacitance (2), is at its maximum [8]. Also, since the data are recorded during the decay of the light pulse and the strongest rate of change of the intensity happens when the module is at the highest range of voltage, the influence of the capacity will be strongest in this phase. In a somewhat simplified view, the capacitance is charged during the unrecorded rise of the flash intensity, and is discharged during the course of data taking. Therefore, at a given instantaneous intensity the voltage will be higher than it would be at the same intensity under stationary conditions. The quasi stationary analysis neglects this fact and overestimates the voltage in this region, as can be seen in the dashed curves in Fig. 5.

Due to the negative slope of the voltage during the recording of the flash (Fig. 2) the capacitance acts as an additional current source (1). The quasi stationary analysis does not consider this, because its least-squares fit (4) does not use the measured current directly, but implicitly attributes to the current at a given intensity a value of $I - C\mathrm{d}V_{\mathrm{int}}/\mathrm{d}t$, which is lower than the actual current of the PV-module. This underestimation of the current can be seen in the dashed curves of Fig. 5 in the horizontal region from short circuit to maximum power condition.

For the parameters of practical interest as listed in the lower half of Tab. I, the two methods give values which are within the error of even the same measurement methods of different laboratories [13]. The stationary analysis overestimates V_{oc} by 2.2%, $V@P_{\mathrm{max}}$ by 0.95% and P_{max} by 0.36%. It underestimates I_{sc} by 1.7% and $I@P_{\mathrm{max}}$ by 0.75%. The difference is especially small with P_{max}, so that for purposes of power rating the quasi stationary method is well justified, and has been employed in a multi-flash scheme already quite some time ago [2].

The situation may be different with PV-modules from mono crystalline silicon or from thin film cells, both of which can have significantly higher capacitances than the PV-module used in this work [5]. We expect that with those technologies only the dynamic parameter extraction method can be applied reliably. These investigations will be part of a future project.

CONCLUSION

We have presented first results of a short-flash and wide-illumination range method for the characterization of PV-modules, which does not require expensive flash-control technology. The physical parameters of the I-V curves and the parameters of practical interest were obtained by means of the time dependent one diode model. We found that, if the capacitances of the PV-module are included as free parameters in the data fit routine, the method gives very trustworthy values of the characteristic parameters of the I-V curve for a range of illumination intensities from approximately 250 to 1600 W/m^2.

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