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RELIABILITY OF ROUTINE 2-DIODE MODEL FITTING OF PV MODULES

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ABSTRACT: Five c-Si PV modules were investigated with the IDCAM method which provides a model to predict the IV curve for any irradiance or temperature from a single measurement. The model predictions are compared to explicit measurements of IV curves at various irradiances and temperatures. A comparison with the method of the international standard IEC60891 for translation of IV curves is also made. It was found that the IDCAM method can predict the IV curves down to 200 W/m^2 and for all expected operating temperatures of the PV module. For large translations it is more accurate than the method prescribed by IEC 60891. The remaining discrepancies between measurements and model point out where the model is to be improved in the future.
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1 INTRODUCTION

Recently a new method for fitting IV curves of c-Si solar cells with a 2-diode model has been presented namely Irradiance Decay Cell Analysis Method (IDCAM) [1]. This method can calculate the IV curves for any combination of temperature and irradiance based on just one single measurement. This single measurement contains an IV curve measured near standard test conditions (STC, here 1000W/m^2 and 25 °C, with the simulator spectrum) and the decay of the open circuit voltage V_{oc} with decaying irradiance of the light flash. The method was extended to PV modules and the reliability of the physical model for predicting module performance is investigated in this paper.

IV curves of c-Si PV modules were measured for a number of combinations of irradiance and temperature. These experimental results were compared to the predictions for the same conditions from IDCAM and also the IEC60891 [2].

2 Methods

2.1 IDCAM for PV modules

Standard QuickSun solar simulators measure the IV characteristics during the falling tail of a Xenon flash pulse. The measurement is triggered typically when the irradiance is at about 15 % above the target irradiance level and during the following two milliseconds the module is swept from short circuit into open circuit. Voltage, current and irradiance signals are recorded each having 512 data points. The module temperature is measured with an accuracy of ±0.5 °C. The IV curve is then translated to STC (1000 W/m^2 and 25 °C, but not spectral mismatch corrected) by using the procedure described in IEC 60891. Since the measurement was triggered already at about 1150 W/m^2, the irradiance correction is almost negligible at maximum power point. With the standard option of QuickSun software the measured IV data points can be translated to any temperature using the procedure of IEC 60891. This option was used in order to find the optimal IEC 60891 parameters by comparing IDCAM characteristics with the extrapolated IEC characteristics at different temperatures.

A well known and physically reliable model for c-Si solar cells consists of five components which are

- i) ideal diode
- ii) recombination diode
- iii) shunt resistance
- iv) series resistance and
- v) current source representing the irradiance stimulated current.

This equivalent circuit has the mathematical form of the following equation (1).

$$I = I_{sun} - I_{diff}\left[e^{\frac{q}{kT}(V+IR_{ser})} - 1\right] - I_{rec}\left[e^{\frac{q}{2kT}(V+IR_{ser})} - 1\right] - \frac{V+IR_{ser}}{R_{shunt}} \tag{1}$$

The power of IDCAM in solving the physically reliable equivalent circuit component values with c-Si cells has been reported previously [1]. In this method the diode parameters are evaluated by measuring the V_{oc} decay during the falling tail of the Xenon flash pulse (Figure 1). This principle excludes the effects of series resistance and is therefore more reliable in finding the true diode parameters I_{diff}, I_{rec} and R_{shunt} than traditional IV graph fitting procedures. After this the only remaining unknown component, series resistance, is evaluated by fitting the initially measured voltage, current and irradiance signals.

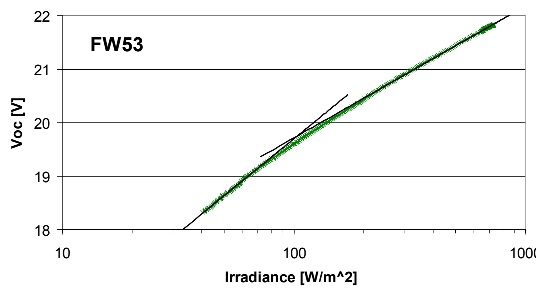

Figure 1: V_{oc} against irradiance measured during the decay (tail) of the Xe flash light pulse. The two lines are least squares fits of a logarithmic function to high and low irradiance values respectively.

Here we have applied IDCAM also for complete PV modules having an array of cells connected in series assuming that they are all similar. The five modules we studied are using cells from Kyocera, Q-cells and RWE and thus different c-Si technologies. It is worth of

noticing that small irradiance deviations do not affect the diode parameters since they are evaluated using only the open circuit voltage signal.
Once we have evaluated the component values of the modules it is straightforward to calculate the IV characteristics at any temperature or irradiance conditions by just applying equation (1).

2.2 Reference measurements at ESTI

IV curves were measured at the European Solar Test Installation (ESTI) with two (Spectrolab and PASAN) single flash Xe large area pulsed solar simulators (LAPSS). The measurements on the Spectrolab were done at 1000 W/m^2 and 25 °C, whereas on the PASAN IV curves were obtained for all combinations of 5 irradiances (1000, 800, 600, 400, 200 W/m^2) and three temperatures (25, 40 and 55 °C). The irradiance variation was achieved by triggering the IV curve sweep (1-2 msec length) at different times during the deay of the light pulse (several tens of milliseconds). The temperature was varied by enclosing the module in a test chamber and heating the chamber with the module inside to the desired equilibrium temperature before the measurements. The effect of the quartz glass window front door of the box was accounted for. The small minor temporal irradiance variations during the acquisition of all IV curves were corrected to the nominal mean irradiances according to IEC 60891.

A difference in short circuit current of about 3.5% was noticed between the QuickSun and ESTI measured IV curves. This can be mainly attributed to the different irradiance sensors and also partly to differences in the simulator spectra . The irradiance measurement of ESTI was used as reference and all other data (Quicksun measurements and IDCAM) were scaled accordingly.

From the measurements the temperature coefficients α and β (for open circuit voltage V_{oc} and short circuit current I_{sc} respectively) were obtained from a linear least squares fit to the data as function of temperature. α was fed into IDCAM, whereas β was compared to the predictions of IDCAM based on the temperature behaviour of Si. Furthermore R_{ser} and the curve correction factor κ were determined according to IEC 60891 and compared with the IDCAM. Translation of measured IV curves was always based on IEC60891, but for the purposes of this paper exceeded the limits of ±30% in irradiance set in the standard itself.

3 RESULTS

The IV curves measured with the Quicksun simulator and at ESTI with the Spectrolab LAPSS are compared with each other and with IDCAM (Figure 2). The curves for 1000 W/m^2 and 25 °C overlay nearly perfectly so that it almost impossible to notice any difference.

Based on this the IV curves as measured at the extreme conditions (200 W/m^2 at 25 °C and 1000 and 200 W/m^2 at 55 °C) are compared (Figure 3 and Figure 4). For 200 W/m^2 and 25 °C the curves differ only slightly in I_{sc} but otherwise overlay perfectly. For 1000 W/m^2 and 55 °C the most noticeable difference is in V_{oc}. Similarly for 200 W/m^2 and 55 °C there seems to be a shift in voltage between the two curves. When starting to work with the model the difference between IDCAM and measured V_{oc} was even larger (Figure 5). The reason turned out to be that we were using rather old Si band gap data [3]. After applying the latest band gap parameters [4] the fit improved substantially. This is to be seen as a direct proof that IDCAM is able to measure the real physical parameters of the cells of even the series connected modules.

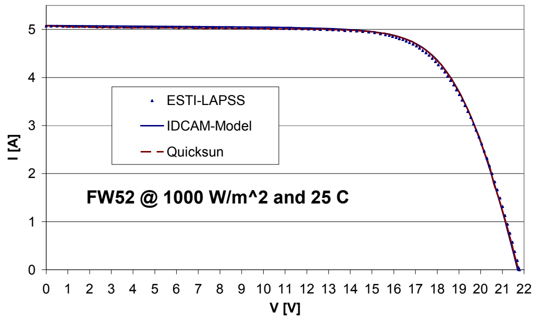

Figure 2: Comparison of experimental IV curve of Quicksun simulator and Spectrolab LAPSS (ESTI) with IDCAM. All three curves overlay nearly perfectly.

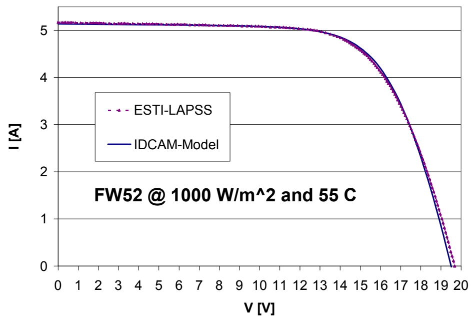

Figure 3: Measurement and IDCAM for 1000 W/m^2 at 55 °C.

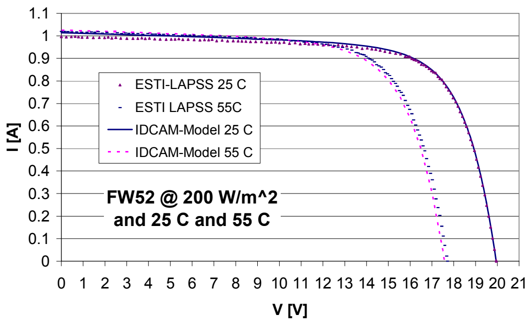

Figure 4: Measurement and IDCAM for 200 W/m^2 at 25 °C and 55 °C.

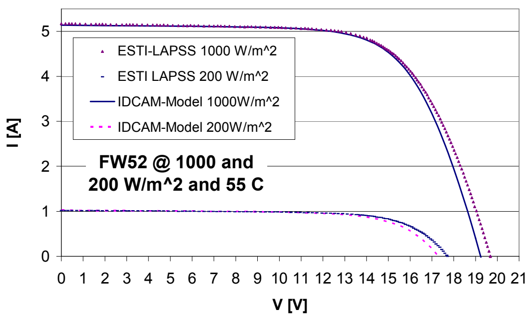

Figure 5: Measurement and IDCAM for 1000 and 200 W/m^2 at 55 °C using old temperature coefficients for Si [3].

The slight deviation between the measurements and IDCAM around the maximum power point suggests an influence of the series resistance, as this part of the curve is particularly sensitive to this parameter. Therefore the series resistance determined from IDCAM (9.8 mΩ/cell) was increased by 10% (10.8 mΩ/cell). The agreement between experiment and model is improved around the maximum power point (Figure 6).

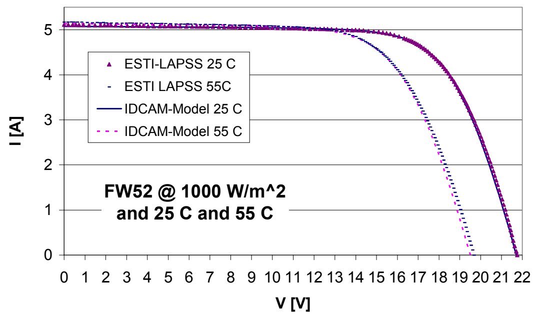

Figure 6: Measurement and IDCAM for 1000 W/m^2 at 25 °C and 55 °C using a series resistance of 10.8 mΩ for the calculation, which is 10% higher than originally determined by the IDCAM (9.8 mΩ).

For large extrapolations the IEC 60891 procedure is not applicable. For test purposes the IV curve measured at 800 W/m^2 and 25 °C was extrapolated to 200 W/m^2 and 55 °C based on α, β, κ and R_{ser} determined according to IEC 60891 (Figure 7). It is clearly seen that the standard is not applicable. Apart from differences in V_{oc} and I_{sc}, there is also a distortion of the curve for low voltages. This is probably due to the approximations made in the standard, whereas IDCAM is based on a physical model of the PV module.

The results shown in examples above were confirmed on the other modules.

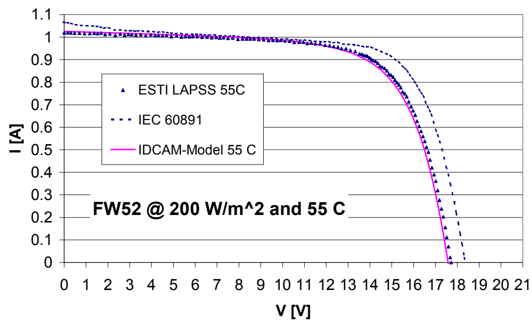

Figure 7: Measurement and IDCAM for 200 W/m^2 at 55 °C compared to IEC 60891 translation from measurement at 800 W/m^2 and 25 °C (using α, β, κ and Rs according to IEC 60891).

IDCAM does not provide α, but this parameter can be approximated as 10 μA/cm^2/K for most cells. In addition, the overall role of temperature correction for current is not of major importance. R_{ser}, α and κ as provided by standard QuickSun measurement cycle with IDCAM option are compared to the values determined according to IEC60891 (Table 1).

The agreement for κ is very good, especially considering that it is very difficult to determine this parameter accurately following IEC 60891. R_{ser} is consistently lower from IDCAM when compared to the value determined using IEC 60891. As was already noted above the fit of IDCAM can be improved if the series resistance value is slightly increased in the model. It has also to be noted that the R_{ser} determined following IEC 60891 gives different values depending on which irradiances are chosen.

Table 1: Temperature coefficients α (in μA/cm^2/K) and β (in mV/K/cell), κ (in mΩ/K/cell), R_{ser} (in mΩ/cell) and R_{shunt} (in Ω) as determined from the measurements following IEC 60891 (index IEC) and as provided by IDCAM (index IDC).

	FW52	FW53	FW54	FW55	FW56
c-Si	Poly	EFG	Poly	Poly	Poly
α_{IEC}	12.1	22.7	14.1	8.8	9.1
β_{IEC}	-1.9	-2.0	-2.0	-1.9	-2.0
β_{IDC}	-2.0	-2.0	-2.0	-2.05	-2.0
κ_{IEC}	0.07	0.1	0.06	0.04	0.04
κ_{IDC}	0.05	0.1	0.04	0.04	0.04
$R_{ser\ IEC}$	13.4	15.4	10.3	7.4	7.9
$R_{ser\ IDC}$	9.8	10.8	6.9	5.4	5.3
$R_{shunt\ IDC}$	9.1	53.1	11.8	6.6	8.6

R_{shunt} as provided by IDCAM is typically 10 Ω. For module FW53 it was 5 times higher. However, the fitting between IDCAM and measurement is better for R_{shunt} = 10 Ω (Figure 8).

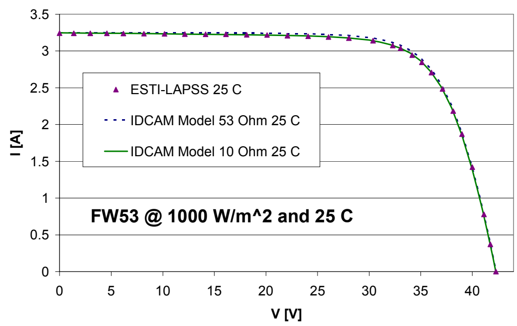

Figure 8: Measurement and IDCAM for 1000 W/m^2 at 25 °C with two different R_{shunt}.

4 DISCUSSION

The international standard IEC 60891 requires several measurements to determine the parameters R_{ser}, α, β and κ in order to translate IV curves from one combination of irradiance and temperature to another and can be summarized as follows (Figure 9):

- translation for irradiance requires R_{ser}. This can be determined from 3 IV curves taken at the same temperature but different irradiances. Note that the translation is limited to ±30% from the irradiance at which the IV curve was measured.

- translation for temperature requires α, β and κ. They can be obtained from 3 IV curves measured at the same irradiance but at different temperatures.

- translation for irradiance and temperature require R_{ser}, α, β and κ. Therefore a minimum of 5 IV curves need to be measured (three irradiances and three temperatures).

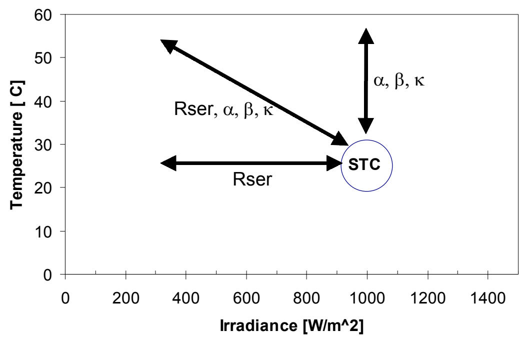

Figure 9: Schematic of IV curve translation according to IEC 60891.

IDCAM on the other hand is based on a single measurement near STC requiring the same time as a simple IV curve measurement. Fitting of the parameters in a physical model describing the module allows than the translation of the IV curves according to equation (1). IDCAM not only overcomes the limitation of ±30% irradiance correction but also reduces the measurement time considerably. This potentially opens up possibilities for in-line energy rating of c-Si PV modules which require the performance surface, i.e. the maximum power as function of irradiance and temperature [8].

While the results from IDCAM and IEC60891 are basically identical for translations allowed according to the standard (±30% in irradiance), there are noticeable differences for larger translations. In this case IDCAM gives clearly the better prediction. Essentially IDCAM is capable of predicting IV curves down to 200 W/m^2 (and probably lower, but this was not investigated) and for all operating temperatures which can be expected.

While investigating the reasons for the higher shunt of FW53 (Figure 8) determined by IDCAM it was found that there is a systematic problem. Correcting this will also change the saturation currents of the two diodes I_{diff} and I_{rec} and the series resistance R_{ser}. The correction will lead to improved fitting, especially at high temperatures close to V_{oc}.

It might also be interesting to compare with the rapid method of determining β from the difference between the band gap at 0 K and a measurement of V_{oc} at any temperature [5]. Furthermore the determination of R_{ser} might require some fine tuning.

Other approaches [6, 7] fit the 2 diode model to the IV curve whereas IDCAM obtains the main information from the decay of the open circuit voltage. It might be interesting to compare the different fitting methods.

5 CONCLUSIONS

IDCAM for c-Si PV modules predicts with good reliability especially the maximum power point value of the IV curves for a large range of irradiance and module temperature. It is also worth of noticing that with IDCAM one does not need to manipulate large data files but just to save and use the equivalent circuit parameters with equation (1). As IDCAM is also a fast method (essentially the same time as for a single IV curve) it has prospects for application in a production line providing further parameters for quality control. Energy rating or energy yield prediction for c-Si is reliable if the performance matrix or surface (i.e. maximum power as function of irradiance and module temperature) is known [8]. IDCAM would allow such a prediction based on a single measurement in the laboratory.

6 ACKNOWLEDGEMENTS

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