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Determination of internal series resistance of PV devices: repeatability and uncertainty

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Abstract

The calibration of photovoltaic devices requires the measurement of their current–voltage characteristics at standard test conditions (STC). As the latter can only be reached approximately, a curve translation is necessary, requiring among others the internal series resistance of the photovoltaic device as an input parameter. Therefore accurate and reliable determination of the series resistance is important in measurement and test laboratories.

This work follows standard IEC 60891 ed 2 (2009) for the determination of the internal series resistance and investigates repeatability and uncertainty of the result in three aspects for a number of typical photovoltaic technologies. Firstly the effect of varying device temperature on the determined series resistance is determined experimentally and compared to a theoretical derivation showing agreement. It is found that the series resistance can be determined with an uncertainty of better than 5% if the device temperature is stable within ± 0.1 °C, whereas the temperature range of ± 2 °C allowed by the standard leads to much larger variations. Secondly the repeatability of the series resistance determination with respect to noise in current–voltage measurement is examined yielding typical values of $\pm 5\%$. Thirdly the determination of the series resistance using three different experimental set-ups (solar simulators) shows agreement on the level of $\pm 5\%$ for crystalline Silicon photovoltaic devices and deviations up to 15% for thin-film devices.

It is concluded that the internal series resistance of photovoltaic devices could be determined with an uncertainty of better than 10%. The influence of this uncertainty in series resistance on the electrical performance parameters of photovoltaic devices was estimated and showed a contribution of 0.05% for open-circuit voltage and 0.1% for maximum power. Furthermore it is concluded that the range of device temperatures allowed during determination of series resistance in IEC 60891 should be further restricted.

Keywords: photovoltaic devices, series resistance, calibration, standard test conditions, uncertainty

(Some figures may appear in colour only in the online journal)

1. Introduction

The series resistance R_S of a solar cell influences the maximum available power of a photovoltaic (PV) device, indicating in

some way the quality of the device [1]. Its determination is therefore of particular interest.

The experimental complexity of a precise measurement is one of the reasons for which a theoretical approach is more frequently used for the derivation of the series resistance. Different theoretical models have been analytically derived from either the one-diode solar cell model or the two-diode solar cell model. However the general trend calculated from



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these methods shows a great deviation in obtained values [2]. Other studies have confirmed that the illumination intensity variation is one of the most reliable and robust way to determine the series resistance under operating conditions [3].

In a reference laboratory for electrical characterization of PV devices, such as the European solar test installation (ESTI) at the joint research centre (JRC) of the European Commission, the experimental determination of the series resistance is of fundamental importance. A theoretical derivation is not possible as the relevant information about the PV device to be measured is not available. Furthermore, for traceable and accredited measurements, the determination of the series resistance necessarily has to follow the international standard IEC 60891 [4].

The accuracy with which R_S is determined has an influence on the accuracy of the official calibration values certifying the electrical performance of PV devices. Therefore, in this work the repeatability and uncertainty of the R_S determination from measured current–voltage (I – V) characteristics is investigated. Then, the influence of this uncertainty (UC) in the R_S value on the electrical performance parameters of PV devices is examined.

It has to be remarked that the knowledge of the internal series resistance of a PV device is not required if the irradiance under which the latter is measured is the same irradiance (or very close to it) at which the electrical performance is to be reported. This condition can be achieved on modern solar simulators. However, on older instruments it might not always be the case. Also, the adjustment of the irradiance of the solar simulator normally goes hand in hand with a change in spectral irradiance. As it is rather difficult to determine the latter to a high accuracy, it might be preferable to operate the solar simulator at fixed irradiances (for which the spectral irradiance has been determined) and rather translate the measured I – V curves. Furthermore, calibration under natural sunlight has several advantages. However, the irradiance cannot usually be chosen or easily adjusted, so that I – V curve translation is normally required. Typical translations are for a difference in irradiance of 50 W m^{-2} , with 100 W m^{-2} being a practical upper limit.

Here, sets of I – V curves have been measured for a representative pool of current PV technologies at different irradiance levels and at different device temperatures by using several solar simulators. The calculation of the series resistance from each set of measured I – V curves has been carried out by means of dedicated software. First, the influence of varying device temperature on the series resistance value as determined from measurements is compared to a theoretical derivation reported in [5]. Secondly, the variation of calculated series resistance due to noise in the I – V curves is investigated by using repeated measurements under nominally identical conditions. Thirdly, the comparison between three different solar simulators used for the measurement of I – V curves is examined. Based on the results the overall uncertainty in R_S determination is estimated and its contribution to the uncertainty in electrical performance parameters of PV devices investigated. To achieve this, measured I – V curves were translated by a fixed irradiance difference, once by using just the average value of R_S and then by including the calculated UC.

The difference in the resulting electrical performance parameters was then analyzed.

2. Materials and methods

2.1. Theory

IEC 60891 ed. 2 (correction procedure 1) defines two equations for I – V curve translation from irradiance G_1 and temperature T_1 to irradiance G_2 and temperature T_2 . For the determination of the series resistance R_S a number N of I – V curves is measured at different irradiances. Then $(N - 1)$ curves are translated to the I – V curve with the highest irradiance (corresponding to the highest short circuit current I_{SC}) using the translation equations and an initial value for the series resistance $R_S = 0$. By changing R_S in steps of $10 \text{ m}\Omega$ in the positive or negative direction, the proper value of R_S is found when the deviation of the maximum output power of all translated I – V curves coincides within $\pm 0.5\%$. The temperature of the PV device should be the same for all N irradiances at which the I – V curves are acquired, however, IEC 60891 allows a variation of $\pm 2 \text{ }^\circ\text{C}$.

A varying temperature will change the I – V curve (due to the temperature coefficients) in the same region, namely between maximum power point (P_{\max}) and open circuit voltage (V_{OC}), as a variation of R_S . Therefore calculating R_S from I – V curves measured at different device temperatures, without taking account of this temperature variation will result in a different R_S than for a set of measurements at constant device temperature. Therefore, calculating R_S from I – V curves measured not only at different irradiances, but also at different device temperatures, results in an R_S value different from that obtained if the device temperature were constant whenever the temperature variation is not taken into account.

The quantitative influence of varying device temperature on determination of R_S has been derived theoretically [5] based on the I – V curve translation equations [4]. For the simpler case of translating I – V curves to the same V_{OC} , the expression for the difference ΔR_S is [5]:

$$\Delta R_S = -\beta_{\text{rel}} \frac{\Delta T}{\Delta G} \frac{V_{OC}^{G_2}}{I_{SC}^{G_1}} \quad (1)$$

with

β_{rel} : relative temperature coefficient for V_{OC} in units of $(\%/^\circ\text{C})$ at irradiance G_2 ;

(G_1, T_1) : irradiance and temperature of the measured I – V curve;

(G_2, T_2) irradiance and temperature of the target I – V curve. G_2 is assumed to be the higher irradiance;

$\Delta T = (T_2 - T_1)$: temperature difference ($^\circ\text{C}$);

$\Delta G = \left(\frac{G_2}{G_1} - 1\right)$: measure of irradiance difference (a-dimensional);

V_{OC} : open-circuit voltage (V);

I_{SC} : short-circuit current (A).

In order to reduce ΔR_S given $V_{OC}^{G_2}$ and $I_{SC}^{G_1}$, ΔT should be minimized and ΔG maximized. Obviously there are limits to

Table 1. Devices under test for temperature variation measurements and related temperature coefficients.

Device	I_{sc} (A) STC	V_{oc} (V) STC	α_{rel} (%/°C)	β_{rel} (%/°C)	κ_{rel} (%/°C)
NUF2 c-Si cell	12.4	0.6	NA	-0.34	NA
ZZ71 c-Si module	4.62	42.92	0.043	-0.35	0.068
TD81 Poly-c-Si module	5.53	41.6	0.061	-0.35	0.066
AY81 a-Si module	1.26	140.82	0.060	-0.31	-0.078

this, as ΔG is typically 0.1 and should never be larger than 0.3. ΔT of ± 2 °C, as allowed by IEC 60891 ed. 2, leads to a deviation ΔR_S of the same order (i.e. 100%) of the R_S itself for typical crystalline silicon (c-Si) devices (as can be calculated from figures reported in table 1, section 2.3). Therefore, absolute ΔT should be much smaller than what prescribed by the standard; ideally ΔT should be maximum ± 0.1 °C (achievable on pulsed solar simulators), so that the values shown above are reduced by a factor of 20, i.e. to about 5% of the series resistance.

Equation (1) was derived minimizing the distance between the I - V curves near V_{OC} , while IEC 60891 [4] requires that the difference in P_{max} (ΔP_{max}) is minimized. The following expression for ΔR_S has been derived in latter case [5]:

$$\Delta R_S = (\kappa_{rel} - \beta_{rel} - \alpha_{rel}) \frac{\Delta T}{\Delta G} \frac{V_{OC}^{G_2}}{I_{SC}^{G_1}} \quad (2)$$

with

κ_{rel} : relative curve correction factor in units of (%/°C) at irradiance G_2 ;

α_{rel} : relative temperature coefficient for I_{SC} in units of (%/°C) at irradiance G_2 .

For typical c-Si PV devices, the parameters κ_{rel} and α_{rel} are both positive and of the same order of magnitude (see table 1), and therefore they can be assumed to cancel each other. Since $-\beta_{rel}$ is significantly larger than either of them (table 1), equation (2) can be approximated by equation (1).

2.2. Software

The series resistance was determined by dedicated software (written in LabVIEW) that performs an analysis based on IEC 60891 ed. 2 [4]. In addition to the procedure for R_S calculation as required by the international standard, it calculates any suitable R_S value that satisfy the criterion on maximum ΔP_{max} for a chosen threshold (0.5% according to [4]) by an optimization procedure that looks for the R_S corresponding to the smallest value of ΔP_{max} [5, 6].

The program performs the analysis with two methods:

- Standard method: the irradiances used for corrections are those measured by the reference cell;
- Self-reference method: if the device is linear with respect to irradiance G , the irradiances of the lower $N - 1$ curves can be computed by using the ratios of their I_{SC} versus the highest I_{SC}^{max} :

$$G' = \frac{I_{SC}'}{I_{SC}^{max}} G^{max} \quad (3)$$

In this way, only the highest irradiance needs to be measured (even approximately, since no accurate value is required), all the others are calculated.

Furthermore, dedicated software has been developed in order to calculate the curve-correction factor κ according to the standard [4], following the same principle and the same structure of the R_S software.

2.3. Experiments

2.3.1. Solar simulators. Three different large-area solar simulators were used, two pulsed (Spire SLP4600 and Pasan IIIB), and one steady-state (All Real Apollo). The Spire system uses two Xenon linear lamps to illuminate the test plane area ($2 \text{ m} \times 1.37 \text{ m}$) with a pulse duration of up to 100ms at 1000 W m^{-2} , while Pasan IIIB has a pulse of 10ms for a test plane area of $3 \text{ m} \times 3 \text{ m}$. The continuous simulator Apollo has eleven Xenon lamps provided with reflectors and secondary optics that irradiate a test area of about $2 \text{ m} \times 2 \text{ m}$.

2.3.2. Measurement at different device temperatures. Several measurements at different device temperatures (between 16 °C and 25 °C) and at different irradiances (between 900 W m^{-2} and 1100 W m^{-2} in steps of 50 W m^{-2}) were performed with Spire on different devices, in order to verify the change in the determined R_S . According to [4] the irradiances used for the determination of the series resistance should cover the range of interest within which the curve translation shall be performed. As the most common application is to correct to standard test conditions, i.e. 1000 W m^{-2} , the irradiance range was chosen symmetrically around this value.

The devices under test are listed in table 1. The coefficients were determined by separate measurements (not shown here). The a-Si module was fully stabilized according to IEC 61646 before measurements were taken.

For each device the measurements at different temperatures and irradiances were combined in order to obtain a variety of values for ΔG and ΔT . Series resistance values were calculated with standard and with self-reference methods for each combination (ΔG , ΔT) and then compared to the reference value, which was obtained from a set of measurements with a stable temperature close to 25 °C.

The theoretical ΔR_S according to equations (1) and (2) was also calculated and compared with the reference.

2.3.3. Repeatability on the same device. The repeatability of the R_S determination in terms of repeated I - V measurements at nominally identical conditions has been checked for the three c-Si devices NUF2, ZZ71, TD81 (see table 2).

Table 2. R_S variation, repeatability study.

	R_S (Ω)							
	Self ref				Standard			
	NUF2-PIIIb (m Ω)	NUF2-Spire (m Ω)	ZZ71	TD81	NUF2-PIIIb (m Ω)	NUF2-Spire (m Ω)	ZZ71	TD81
Average	5.220	5.460	0.972	1.020	5.178	5.100	0.965	1.051
Std dev	0.028	0.155	0.040	0.015	0.100	0.057	0.015	0.013
Max dev ΔR_S	0.77%	3.47%	-8.09%	-2.69%	-2.08%	-1.81%	-2.54%	1.61%

Table 3. R_S variation, different set up repeatability study.

Module	Technology	R_S (Ω)				ΔR_S		
		Spire	PIIIB	Apollo	Average	Spire	PIIIB	Apollo
NUF2	Poly c-Si	0.00535	0.00523	N.A.	0.00529	1.13%	-1.13%	N.A.
ZZ71	Mono c-Si	0.916	0.88	0.92	0.905	1%	-3%	2%
TD81	Poly c-Si	1.003	0.956	1.042	1.0003	0.27%	-4%	4%
AY81	a-Si	15.45	17.15	16.04	16.213	-5.78%	4.71%	-1.07%
RM81	Mono c-Si HIT, high efficiency	0.434	N.A.	0.5	0.467	-7.01%	N.A.	7.01%
RM82	Poly c-Si	0.442	0.465	0.448	0.452	-2.14%	2.95%	-0.81%
RM83	Mono c-Si, high efficiency	0.618	N.A.	0.623	0.62	-0.4%	N.A.	0.4%
RM84	Poly c-Si	0.325	0.34	0.336	0.334	-2.6%	1.9%	0.7%
RM85	CIGS	5.96	5.71	4.96	5.543	7.52%	3.01%	-10.52%
RM86	CIGS	2.01	1.99	1.56	1.853	8.45%	7.37%	-15.83%
RM87	CdTe	N.A.	3.2	3.32	3.26	N.A.	-1.84%	1.84%

2.3.4. Repeatability on different systems. A study on the consistency of the values calculated for R_S from measurements executed at all three solar simulators has been carried out for the c-Si devices NUF2, ZZ71 and TD81, for the a-Si thin-film module AY81 and for seven further PV modules comprising two conventional c-Si, two high efficiency c-Si, two CIGS and one CdTe (RM81-RM87, see table 3).

The temperature was normally stabilized close to 25 °C. For NUF2, ZZ71, TD81 and AY81 the I - V curves were measured on Spire at irradiances between 900 W m⁻² and 1100 W m⁻² in steps of 50 W m⁻²; on Pasan IIB at the same irradiances and additionally at 200 W m⁻², 400 W m⁻² and 700 W m⁻² depending on the device; on Apollo they were measured at 600 W m⁻², 800 W m⁻² and 1000 W m⁻².

For RM8x devices the irradiances were set between 800 W m⁻² and 1100 W m⁻² in steps of 100 W m⁻² on Spire and at 800 W m⁻², 1000 W m⁻² and 1100 W m⁻² on Pasan IIB and Apollo.

3. Results

3.1. Validation of theoretical derivation for variation in device temperature

Figures 1–4 plot $\Delta R_S/R_S$ as a function of ΔT for the c-Si devices and the a-Si module. The theoretical ΔR_S and the ΔR_S determined by standard and self-reference methods from the measurements are compared with respect to the common reference value of R_S . The plots display both differences, the relative values as calculated from measurements (i.e. experimentally) and those as calculated based on theoretical assumptions.

According to equations (1) and (2), the signs of ΔG and ΔT determine the sign of ΔR_S . When ΔG and ΔT have different signs, ΔR_S is negative; when they have same sign, ΔR_S is positive. For example, if an I - V curve is translated from a lower to a higher irradiance (ΔG positive) and the latter I - V curve has been measured at a higher temperature (ΔT positive), ΔR_S will be positive, i.e. R_S will be overestimated. If, on the other hand, the I - V curve at higher irradiances was measured at a lower temperature (ΔT negative) ΔR_S will be negative and R_S will be underestimated. For the three c-Si devices the triplets of standard ΔR_S , self-reference ΔR_S and theoretical ΔR_S are generally very close to each other. This was also for the outcome of the calculation of ΔR_S with both equations (equation (1), shown in figures, and equation (2), not shown), as the values of α_{rel} and κ_{rel} are close to each other (table 1).

For module AY81 (a-Si) the analysis has been done following equation (2) because κ_{rel} is negative (see table 1). Also, only the self-reference method is used as the standard method does not work due to the varying spectral mismatch. Again, reasonable agreement is found confirming equation (2) experimentally.

The general agreement between the values determined experimentally and the theoretical calculation confirms the validity of the latter.

3.2. Repeatability of R_S determination

Table 2 shows the variation of R_S calculated from repeated I - V measurements at nominally identical conditions. Obviously

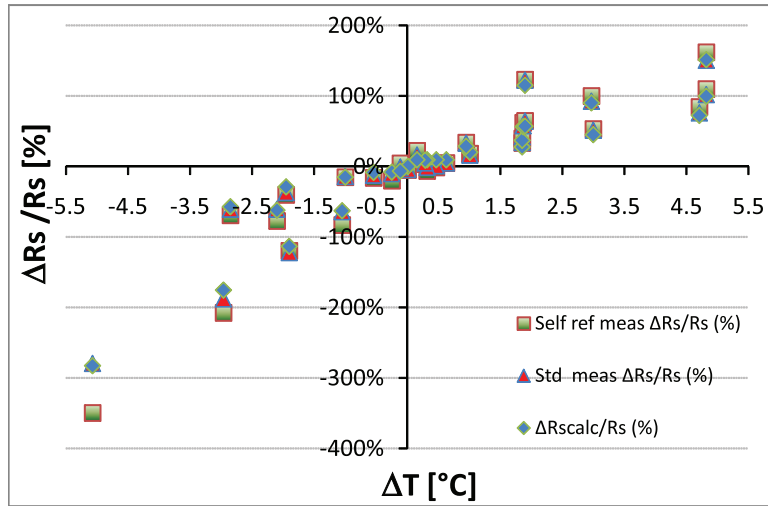


Figure 1. NUF2: ΔR_S as a function of ΔT , comparing the difference observed experimentally with that calculated theoretically.

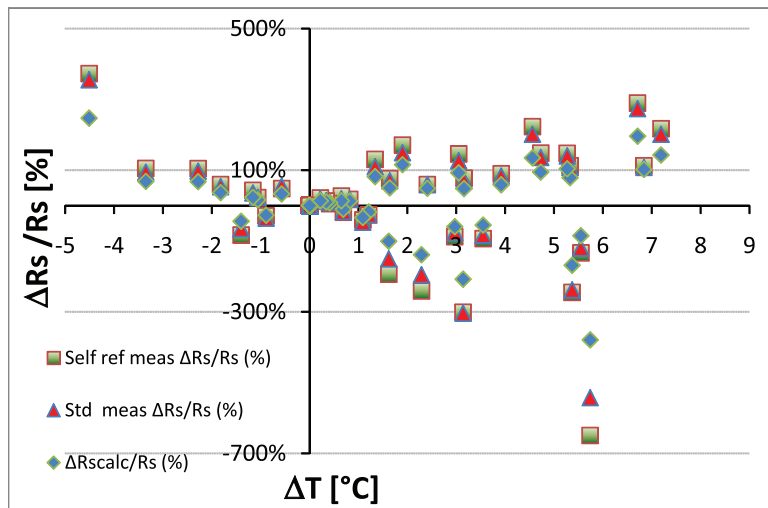


Figure 2. ZZ71 ΔR_S as a function of ΔT , comparing the difference observed experimentally with that calculated theoretically.

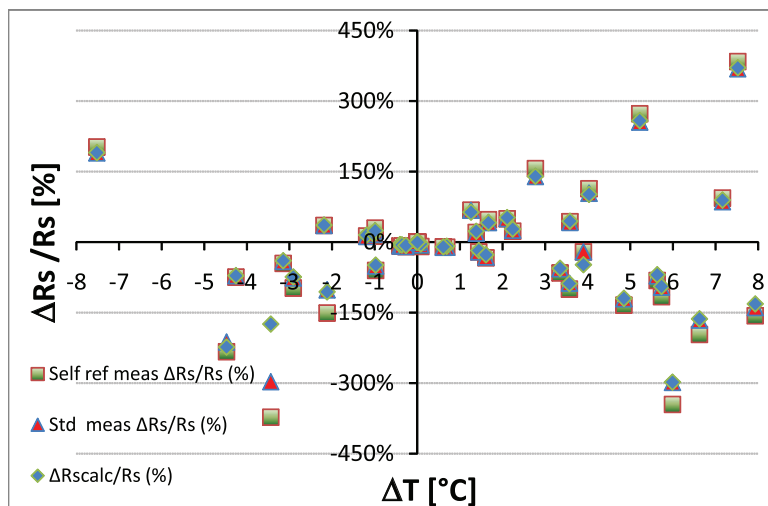


Figure 3. TD81 ΔR_S as a function of ΔT , comparing the difference observed experimentally with that calculated theoretically.

random noise is present in the measured $I-V$ curves. On our systems the noise in $I-V$ curves was determined from the variability of data points in separated $I-V$ curves under

nominal identical conditions. Typical standard deviations for the measurements used here were $\pm 0.04\%$ for the voltage and $\pm 0.03\%$ for the current. The use of repeated $I-V$ curve

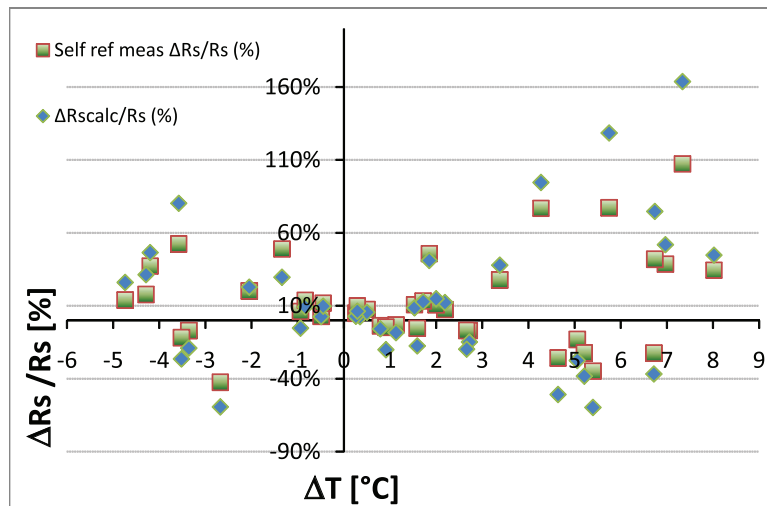


Figure 4. AY81 ΔR_S as a function of ΔT , comparing the difference observed experimentally with that calculated theoretically.

measurements to calculate R_S and its variability shows the sensitivity of the R_S value to the typical noise present in our measurement set-up.

Regarding the single cell (NUF2), the measurements were performed at stable temperature on the same day with Pasan IIIB and on two different days on Spire. In the first case, R_S has been calculated from two sets of consecutive $I-V$ measurements (each including three irradiances) and from all their possible combinations (in total 8). From these combinations the average R_S (including standard and largest deviations) and the deviation of each single value from this average have been determined. The repeatability of R_S is better than 2%, this variation being due to the noise in the $I-V$ curves. In the second case, the deviation between the two measurement sets (one for each day) is 3.47%.

Regarding the two modules, R_S has been calculated from three sets of consecutive measurements (each including three irradiances) and from all possible combinations (in total 27). The measurements were performed on the same day at a stable temperature with Spire.

Considering the data from both modules it is found that the variation of R_S based on repeatability of $I-V$ measurements at nominally identical conditions (i.e. with only typical random noise present) is typically better than 5%, with the worst case around 8%.

3.3. Variation between systems

The repeatability study on different setups is presented in table 3 only for the self-reference method. All values of series resistance determined from the measurements on any of the three systems were considered equally valid. The difference of each result with respect to the average of all measurements was then determined.

For NUF2 the measurements of Apollo were not available due to technical problems with the simulator. For modules RM81 and RM83 the measurements with Pasan IIIB were not feasible since the duration of its flash is too short. Measurements on RM87 were taken with Pasan IIIB and Apollo after module stabilization according to IEC 61646.

4. Discussion

The first part of this investigation (section 3.1) showed that temperature variation in the PV device during $I-V$ curve measurements for determining R_S is potentially the major contribution to uncertainty in the R_S value. The comparison between ΔR_S as determined from measurements and from theory showed good agreement. Hence the theoretical equations (1) and (2) can be used to estimate the expected deviation based on experimental parameters and on the expected temperature variation. For c-Si devices typical parameters show that the variation of the series resistance for a temperature variation of ± 2 °C is of the same order of the series resistance itself, i.e. a deviation of 100%. The solution to this is to reduce the temperature variation (i.e. to increase the stability of the device temperature), since ΔR_S is linear in ΔT (see equations (1) and (2)). On pulsed solar simulators a stability of ± 0.1 °C should be easily reachable, thereby limiting the variation in series resistance to less than 5%. The importance is temperature stability, not the accuracy with which this temperature can be determined nor the homogeneity across the PV device (in case of a module), as long as the latter is stable in time. The time required to measure three $I-V$ curves at three different irradiances is typically less than 2 min. In a temperature controlled room the PV device temperature is expected to change within this time interval by much less than 0.1 °C, as the (short) light pulse is not significant in terms of heating. The situation changes for continuous simulators. With careful management of the room and illuminating the PV device only for a few seconds for each measurement, it is estimated to be able to keep the device temperature within ± 0.5 °C. This invariably will lead to a larger variation in R_S .

It is worthy to stress that the key factor is the temperature stability, and not whether the actual device temperature is exactly a certain value (e.g. 25 °C in case of PV calibration at STC), as the series resistance is not expected to vary significantly with temperature for temperature intervals of a few degrees, as investigated previously [6]. It is interesting to note that also for the large-area steady-state solar simulator, where temperature variations are expected to be larger

(typically ± 0.5 °C) the determined R_S values agree with those of the pulsed solar simulators to within a few percent. Also the dependence of R_S on the irradiance has been shown to be small in the range 800–1000 W m⁻² [6]. Therefore this effect is neglected here. Effectively the procedure in IEC 60891 yields an average value of R_S for the irradiances range used for its determination. If R_S is of interest for an irradiance outside this range it should be determined by a separate measurement.

Based on this, an amendment to the standard IEC 60891 [4] is strongly recommended for its next edition. Either a much narrower temperature range should be defined or a correction procedure implemented to take account of device temperature variations. In any case the standard should clearly point out that the temperature variations are a significant factor for the uncertainty in series resistance determination.

In the second part of this paper the repeatability of the R_S calculation was investigated by looking at the variability due to I - V curves nominally identical, but obviously subject to experimental noise. The repeatability was typically better than 5%. It should be noted that part of this variation might also be due to temperature non-uniformity across the PV device. The device temperature is measured only at a single point of a large-area module, so even for the same measured temperature the average device temperature might vary by ± 0.1 °C, which would give a variation in series resistance of similar size (see section 2.1).

Eventually, in the third part it was shown that also measurements performed at different solar simulators can result in equivalent values of series resistance. For c-Si technologies (including high-efficiency ones) a reproducibility of better than 5% was found. For thin-film technologies the PV device stability has to be considered in measurements in general as well as for the determination of the series resistance. The a-Si (AY81) and the CdTe (RM87) modules were both stabilized according to IEC 61646 before determining the series resistance and its variation was again 5% or less.

CIGS devices (RM85 and RM86) are known to have a different stability issue. Essentially the measurement results depend on the illumination history immediately prior to the measurement. The latter is different for pulsed simulators (module in dark just before measurement) and steady-state simulators (module fully illuminated just before measurement). This is confirmed here also for the results of series resistance determination. The two pulsed systems (Spire and Pasan IIIB) agree with each other to better than 5%, whereas the result obtained with the continuous solar simulator (Apollo) is lower by up to 15%. However, the measurements for I - V parameters are known to be more reliable on the steady-state solar simulators; therefore, the series resistance determined with the Apollo is thought to be the most appropriate.

The results of self-reference and standard methods might differ, in particular when there are effects such as a varying spectral mismatch due to variation of the spectral irradiance at different irradiance levels. The latter is not uncommon when the irradiance level of a solar simulator is changed. This is usually achieved by varying the lamp discharge voltage, which is known to affect spectral irradiance of the lamp. In the case of a well matched reference device (typically c-Si technology) to

the device under test (i.e. the latter also being c-Si technology) both methods work. For other cases such a match is not given (i.e. a-Si module) and therefore the spectral irradiances and hence the spectral mismatch factor will vary during a set of measurements including different irradiances. To correct for this effect would require a measurement of the light spectrum at each irradiance, which is rather difficult. Therefore, in these cases (and in effect in general) it is recommended to use the self-reference method, which auto-corrects for the effect for linear devices.

From the results it is estimated that the overall accuracy of R_S determination is about 10% for c-Si technologies as well as for those thin-film technologies that can be stabilized (a-Si and CdTe). For CIGS thin-film technologies, whose electrical performance depends on the illumination path followed just before the I - V measurements, higher variations between pulsed and steady-state solar simulator of up to 15% were found.

This is not yet a rigorous and fully exhaustive derivation of the uncertainty in R_S determination. However, so far the calculation of the uncertainty in R_S determination has not been addressed at all and therefore this estimate is useful as starting point, for example serving as input for the successive calculation of the uncertainty of PV performance as determined after I - V curve translation, which may require the series resistance as one input parameter.

In order to evaluate the effect of the uncertainty in R_S value on the electrical performance parameters, the following calculations were made. For each device in table 3 one experimental I - V curve was translated by 50 W m⁻² and 100 W m⁻² with four different values of the series resistance R_S , namely 0 Ω (i.e. simulating the case where the series resistance is neglected), the average value (taken from table 3) and the latter varied by $\pm 10\%$.

The following table 4 shows the variation in the three main electrical performance parameters I_{SC} , V_{OC} and P_{max} with respect to the reference value taken as that determined with the average series resistance value.

It is seen that the variation of I_{SC} is negligible in all cases. The variation in V_{OC} ranges from $\pm 0.029\%$ to $\pm 0.074\%$ for an I - V curve translation of 50 W m⁻² and a variation in R_S by $\pm 10\%$. For a translation of 100 W m⁻² the differences are twice as large, and for neglecting R_S (corresponding to 100% change in R_S) it is 10 times larger. Such a linear behavior is to be expected from the curve translation equations [4]. For both I_{SC} and V_{OC} the behavior is symmetric in the sense that a variation of R_S in opposite directions leads to a deviation in the opposite direction for I_{SC} and V_{OC} and of the same size. For P_{max} the latter becomes asymmetric. The deviations for a variation of R_S by $\pm 10\%$ lead to variations ranging from -0.087% to 0.135% . When neglecting R_S this becomes -0.948% to 0.753% . The corresponding values for a translation of 100 W m⁻² are larger, ranging -0.183% to 0.171% for $\pm 10\%$ of R_S and -1.85% to 1.465% when neglecting R_S altogether.

Based on this sample it can be summarized that I_{SC} does not vary with R_S , V_{OC} varies typically by $\pm 0.05\%$ (for 50 W m⁻² translation) and P_{max} by 0.1% if R_S varies by $\pm 10\%$. If R_S is neglected the variations in V_{OC} are 10 times larger, and for P_{max}

Table 4. Variation of electrical performance parameters short circuit current I_{SC} , open circuit voltage V_{OC} and maximum power P_{max} with respect to the reference value taken as that determined with the average series resistance value for two different irradiance translations (50 W m^{-2} and 100 W m^{-2}) and three values of series resistance, $0\ \Omega$ and average $\pm 10\%$.

Device	$\Delta G\ (\text{W m}^{-2})$	50			100		
		$\Delta I_{SC}\ (\%)$	$\Delta V_{oc}\ (\%)$	$\Delta P_{max}\ (\%)$	$\Delta I_{SC}\ (\%)$	$\Delta V_{oc}\ (\%)$	$\Delta P_{max}\ (\%)$
NUF2	$R_S = 0$	-0.0022	-0.568	-0.745	-0.0047	-1.148	-1.485
	$R_S + 10\%$	0.0002	0.057	0.082	0.0005	0.115	0.146
	$R_S - 10\%$	-0.0002	-0.057	-0.062	-0.0005	-0.115	-0.163
ZZ71	$R_S = 0$	0.0017	-0.469	-0.589	0.0036	-0.965	-1.249
	$R_S + 10\%$	-0.0002	0.047	0.076	-0.0004	0.096	0.109
	$R_S - 10\%$	0.0002	-0.047	-0.024	0.0004	-0.097	-0.145
TD81	$R_S = 0$	-0.0316	-0.646	-0.815	-0.0662	-1.292	-1.659
	$R_S + 10\%$	0.0032	0.065	0.132	0.0066	0.129	0.165
	$R_S - 10\%$	-0.0031	-0.065	-0.084	-0.0066	-0.129	-0.149
AY81	$R_S = 0$	-0.0373	-0.744	-0.948	-0.0789	-1.473	-1.850
	$R_S + 10\%$	0.0037	0.074	0.126	0.0080	0.147	0.171
	$R_S - 10\%$	-0.0037	-0.074	-0.087	-0.0079	-0.147	-0.183
RM81	$R_S = 0$	0.0023	-0.395	-0.496	0.0048	-0.788	-0.946
	$R_S + 10\%$	-0.0002	0.039	0.073	-0.0005	0.079	0.126
	$R_S - 10\%$	0.0002	-0.039	-0.044	0.0005	-0.079	-0.078
RM82	$R_S = 0$	0.0024	0.423	0.538	0.0046	0.844	1.071
	$R_S + 10\%$	-0.0003	-0.042	-0.021	-0.0005	-0.084	-0.105
	$R_S - 10\%$	0.0002	0.042	0.079	0.0005	0.084	0.108
RM83	$R_S = 0$	-0.0092	-0.295	-0.360	-0.0195	-0.593	-0.712
	$R_S + 10\%$	0.0009	0.029	0.052	0.0019	0.059	0.080
	$R_S - 10\%$	-0.0009	-0.029	-0.035	-0.0019	-0.059	-0.061
RM84	$R_S = 0$	-0.0020	-0.366	-0.470	-0.0041	-0.751	-0.992
	$R_S + 10\%$	0.0002	0.037	0.065	0.0004	0.075	0.072
	$R_S - 10\%$	-0.0002	-0.037	-0.048	-0.0004	-0.075	-0.145
RM85	$R_S = 0$	0.0029	-0.523	-0.625	0.0060	-1.070	-1.350
	$R_S + 10\%$	-0.0003	0.052	0.135	-0.0006	0.107	0.096
	$R_S - 10\%$	0.0003	-0.052	-0.046	0.0006	-0.107	-0.143
RM86	$R_S = 0$	0.0149	0.474	0.669	0.0284	0.953	1.311
	$R_S + 10\%$	-0.0015	-0.047	-0.013	-0.0029	-0.095	-0.135
	$R_S - 10\%$	0.0015	0.047	0.100	0.0028	0.095	0.159
RM87	$R_S = 0$	-0.0023	0.570	0.753	-0.0043	1.132	1.465
	$R_S + 10\%$	0.0002	-0.057	-0.074	0.0004	-0.113	-0.140
	$R_S - 10\%$	-0.0002	0.057	0.092	-0.0004	0.113	0.144

they range up to about 1%. For translations of 100 W m^{-2} these typical values are roughly doubled. Typical overall uncertainties in the calibration of PV devices are 0.5% for V_{OC} and 1–2% for P_{max} . Hence, if the curve translation (50 W m^{-2}) is made without $R_S (=0\ \Omega)$ the uncertainty contribution is of the same order as the overall uncertainty and therefore a significant component. If R_S is actually used in the curve translation and its uncertainty is $\pm 10\%$, then the contribution of this to the overall uncertainty becomes a minor contribution. It follows that the determination of R_S is required if typical curve translations of 50 W m^{-2} are made, but that the determination of the R_S value to $\pm 10\%$ is sufficient to not significantly contribute to the overall uncertainty of the final electrical parameters.

One possible interpretation of table 3 would also be to determine for each device which of the three simulators gives the smallest deviation from the average and use that for the determination of the series resistance. However, this leads to

no general rule, as for c-Si technologies the best simulator varies between devices. Also if repeated the best simulator might be a different one, as the variation in repeatability is of the same order of the variability between simulators. Given the limited influence of series resistance uncertainty on uncertainty of electrical performance parameters, the important aspect is that all simulators give series resistance values which are equivalent and therefore the series resistance can be determined on any convenient system.

5. Conclusions

Three aspects of experimental contributions to variation in the determination of series resistance of PV devices were investigated. The temperature variation of the PV devices has a major influence on uncertainty but with careful device temperature control it can be contained to 5%. The noise present in I - V

curves was shown to lead also to a variation in series resistance of 5%. Finally a comparison between various solar simulator systems showed repeatability of typically 5%, except for CIGS thin-film technologies, which showed variations of up to 15%. Overall uncertainty for the determination series resistance of $\pm 10\%$ is deduced from these experimental results. A sensitivity analysis showed that the effect of $\pm 10\%$ variation of R_S on the electrical parameters for an I - V curve translation of 50 W m^{-2} is typically $\pm 0.05\%$ for V_{OC} and $\pm 0.1\%$ for P_{max} and therefore a minor contribution to overall uncertainty.

It is recommended to limit the allowed temperature range for determination of series resistance in IEC 60891, as the current value of $\pm 2 \text{ }^\circ\text{C}$ can introduce a variation as large as the series resistance itself.

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