Research Article

Optimal I-V Curve Scan Time of Solar Cells and Modules in Light of Irradiance Level

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1. Introduction

The I-V curve measurement is an essential performance characterization technique for solar cells and modules as two-terminal DC generators. Either in dark or under illumination, the measurement concept is simple: during the sweep of the terminals of the device under test (DUT) from open circuit to short circuit or vice versa, voltage and current should be measured in quasi static conditions. It can be mistakenly assumed that PV generators exhibit negligible internal capacitance. In particular, the last generation thin film solar cells (SCs) and high-efficiency crystalline silicon SCs exhibit extremely high internal capacitances [1]. The internal capacitance together with the series, parallel, and diode differential resistance form an RC circuit that introduces a transient time constant into the measurement process. The time constant determines the quasi static condition. Its magnitude depends on various parameters such as the operating point (voltage and current), temperature, irradiance level, minority carrier lifetime, and other semiconductor parameters only to mention the most important ones.

While sweeping the I-V curve from point to point, the transient behaviour needs to fade out prior to the measurement being error-free. The charge of the capacitor in the DUT needs to equalize at every point of the measurement. An inappropriate I-V scan time can introduce a significant error into the I-V measurement. When the targeted error is to be kept below a predefined threshold, the I-V curve scan time is downward limited and determined by the SC's dynamic properties. On the other hand, there are several factors determining the scan time upper limit. Foremost, the scan time is dictated by the I-V curve measurement device. For resistive/semiconductor-based curve tracers, the upper limit is defined by the safe operating area (SOA) of the load (usually an MOSFET). For capacitive curve tracers, the capacitor charging time is a fixed quotient of the measurement load capacitance and the current capabilities of the DUT. At indoor measurements, the I-V curve scan
time is upward limited by the duration of homogenous light pulse guaranteed by a flash solar simulator. Measurements under a continuous solar simulator or under the sun can further suffer from errors induced by radiation heating of the specimen [2]; thus, the scan time should not be too long.

To sum up, the optimal scan time should be as short as possible but long enough for the dynamic error to be kept below the predefined error threshold. A too short scan time can be easily detected by scanning the curve in both directions [3]: forward—a scan from short circuit current $I_{SC}$ to open circuit voltage $V_{OC}$; reverse—from $V_{OC}$ to $I_{SC}$. A hysteresis can be observed demonstrating underestimation of the real $I$-$V$ curve in the forward direction and overestimation in the reverse direction (Figure 1(a)).

The resulting error cannot be eliminated neither by averaging both $I$-$V$ curves by voltage nor summing the errors (determined by the error function given in Section 2) of both scan directions (Figure 1(b)). In particular, at too short scan times, the mismatch is high due to $RdI/dt$ term, where $R_s$ is the series resistance of the DUT. The term that determines the error at a fixed time constant value varies at different sweep directions [3]. Furthermore, in several cases (capacitive or inductive load), the detection of the error by sweeping in both directions is not applicable; thus, the determination of required scan time or characterization of dynamic error is even more important.

Measurements under solar simulators are based on a calibrated light source that emits as close as possible to 1000 W/m² as specified in the standard test conditions (STCs) [4]. However, in measurements under the sun, the irradiance levels can vary over a broad range. The IEC 60409-10 standard defines the procedures for scaling the $I$-$V$ curves to STC [5], but does the irradiance level impact the $I$-$V$ measurement error or is there a need for a different scan time? We will address these aspects in our quest for the optimal scan time.

The hysteresis and the effect of the capacitive character of solar cells are well known and reported [3, 6]. Several variations of the dynamic model exist, where most authors use a one-diode model including one or two capacitances [1, 6, 7], while one author uses a two-diode model and two capacitances [8]. None of the presented models were applied and verified on different solar cell technologies. Our previous research has shown that a two-diode model should be used for the optimal extraction of the junction capacitance [9]. The aim of this paper is to analyse the $I$-$V$ curve error of a solar cell or module under test in light of scan time and irradiance level. The analysis is accomplished through SPICE simulation utilizing a two-diode model extended by two nonlinearly bias-dependent capacitors modelling the dynamic character of PV generators. A method for parameter extraction of the presented extended model is developed and evaluated. Whether the model suitably characterizes not only solar cells but also PV modules is discussed in theory and practice. An algorithm for scan time determination is developed, and finally the influence of the irradiance level on the $I$-$V$ curve scan time and error is revealed. Results are demonstrated on three different solar cells of three different technologies: polycrystalline silicon (pc-Si), monocrystalline silicon (mc-Si) and back-contacted monocrystalline silicon (BC mc-Si).

2. Measurement and Modelling Methodology

2.1. Error Determination. The optimal scan time is the minimal time at which the error between a reference curve measured in true quasi static conditions and a curve under the influence of a transient error does not exceed a predefined error threshold. Determination of the error between the reference and the compared $I$-$V$ curve is an essential yet delicate procedure that needs to be established for further analysis. The comparison of $I$-$V$ curves is difficult due to the wide curve slope span $dI/dV$ from $I_{SC}$ to $V_{OC}$. Neither the current difference at equidistant voltage intervals nor the voltage difference at equidistant current intervals is appropriate. A possible comparison quantity is the maximum peak power $P_{mpp}$, although it only relates to single points on both curves and does not provide alignment information of the entire $I$-$V$ curve. We suggest a method that delivers overall $I$-$V$ curve comparison, with the error equally weighted throughout the curve form $I_{SC}$ to $V_{OC}$.

Let the reference curve be stored in the $M_{IV}$ matrix, and let the compared curve be stored in the $N_{IV}$ matrix, where $I$ denotes the current, and $V$ denotes the voltage column of the two-column matrices. The error is derived from a perspective of the available power of the PV generator at a specified load. The points for error calculation are selected as two intersections of a variable linear resistive load characteristics and both curves being compared (ith point $O_{IV}(i)$ on the reference and jth point $N_{IV}(j)$ on the compared curve, Figure 2).

The characteristics of the variable resistive load is defined as $I = g(i) \cdot V$. Foremost, the vector $g$ is calculated as $g(i) = N_{i}(i)/N_{V}(i)$ for each of $N$ points of the compared curve. The reference curve is defined discretely; thus, interpolation is required. For every line $I = g(i) \cdot V$ going through the $N_{IV}(i)$, the intersection point on the reference curve is interpolated (1st order) from the nearest points ($M_{IV}(j)$ and $M_{IV}(j + 1)$) and stored into the $O_{IV}(i)$ matrix. Finally, the components of the error vector can be calculated from $N_{IV}(i)$ and $O_{IV}(i)$ point pairs:

$$E(i) = \sqrt{\frac{(N_{V}(i) - O_{V}(i))^2}{V_{OCCref}} + \frac{(N_{I}(i) - O_{I}(i))^2}{I_{SCref}}}, \quad i = 1, \ldots, N,$$

where $V_{OCCref}$ and $I_{SCref}$ denote the open circuit voltage and the short circuit current of the reference curve.

The maximum value of the error vector $E = \max(E(i))$ is chosen as a qualitative comparison factor to obtain information on the maximum error between the two curves with $i$ typically appearing close to the maximum power point (also seen in Figure 1).

2.2. The Solar Cell Model. The concept of scan time determination is based on a two-diode solar cell model extended by two parallel capacitances modelling the dynamic processes in
The I-V curve hystereses due to the forward and reverse sweep (a) and the corresponding errors caused by the internal capacitance (b) of a back-contacted monocrystalline silicon solar cell (arrows indicate the direction of the sweeps).

The capacitances $C_d$ and $C_j$ determine the dynamic properties of the SC under investigation. Assuming an abrupt $p^+\cdot n$ or $n^+\cdot p$ junction, an analytical approximation of the $C_j$ is derived from the $C_j(V_d) = -dQ/dV_d$ equation [10]:

$$C_j(V_d) = \frac{C_{j0}}{\sqrt{1 - V_d/V_{bi}}}; \quad V_d < V_{bi}; \tag{2}$$

where $C_{j0}$ is the junction capacitance at zero applied voltage, $V_d$ is the internal solar cell voltage, and $V_{bi}$ is the built-in potential. Such voltage-dependent capacitance, although limited as $V$ approaches $V_{bi}$, is implemented into the SPICE diode model.

The $C_d$, as the key component of the SC’s forward-biased dynamic character, is an outcome of minority charge carrier storage in the neutral region and its diffusion ability. $C_d$ is proportional to the base minority carrier lifetime $\tau_d$. For $V_d \gg kT/q$ (forward-biased solar cell), the $C_d$ can be written as a function of temperature, applied voltage, and carrier lifetime using the following simplified equation [10]:

$$C_d(V_d) = \frac{q^2}{2n_1kT}I_d(V_d)\tau_d = \frac{q}{2n_1kT}I_{Sed}V_d/V_{bi}kT\tau_d, \tag{3}$$

where $q$ is the electron charge, $\tau_d$ is the effective diode base minority carrier lifetime, and $I_{Sed}(V_d/V_{bi}kT)$ is the diode forward DC current. In the voltage range where $C_d\geq C_j$, the forward current of the diode $D_1$ is a few orders of magnitude higher than that of $D_2$; thus, only the current of the diode $D_1$ can be used in (3).

Measurement of $C_d$ using direct C-V measurement is aggravated due to high solar cell currents in forward bias. More often, $C_d$ is calculated from (3), while the lifetime $\tau_d$ is measured using one of the following methods: reverse recovery [11], short circuit current decay [12], or open circuit voltage decay (OCVD) [8]. During the OCVD measurement, the charge stored in the SC structure diminishes through

**Figure 1:** The I-V curve hystereses due to the forward and reverse sweep (a) and the corresponding errors caused by the internal capacitance (b) of a back-contacted monocrystalline silicon solar cell (arrows indicate the direction of the sweeps).

**Figure 2:** Error calculation geometry for a forward sweep.

**Figure 3:** Two-diode solar cell model extended by two capacitances.
different loss mechanisms. The OCVD measurement starts with application of a predefined external current or voltage (forward bias) to the device under test (DUT). At \( t = 0 \), the forward bias is abruptly switched off. The voltage decay on the DUT’s terminals is measured as the charge stored within the DUT diminishes with time. Voltage should be monitored as close to the DUT as possible to avoid the error caused by the series resistance of the measurement setup.

Three characteristic regions can be defined when analysing the OCVD signal of crystalline silicon SCs (see Figure 5 for OCVD shapes of different technologies) [13]:

(i) the voltage drop due to the lumped series resistance,
(ii) the quasilinear region due to the charge storage in neutral region (diffusion component),
(iii) the exponential decay that starts with the diffusion capacitance dropping below the junction capacitance. The charge stored in the space charge region is released through the recombination process and the lumped shunt resistance \( R_{sh} \).

With both capacitances implemented and the static two-diode model parameters determined, we will present a method to extract both the \( \tau_d \) and the \( C_{j0} \) parameters from the OCVD signal.

2.3. Extended Model Parameter Extraction. Two basic measurements—the \( I-V \) characteristic and the OCVD signal—are required for determination of the parameters of the extended model shown in Figure 3. As the OCVD signal is measured without the illumination, the method gives best results with the dark quasi static \( I-V \) measurement. Only the extraction of the photo-generated current \( I_{ph} \) is required under illumination.

Our measurement setup consists of an \( I-V \) curve tracer and an OCVD measurement setup. The curve tracer is constructed from parallel connection of three independent channels of two Keithley SMU 2602A units. One channel is configured as a voltage source determining the measurement voltage, whereas the other two channels are configured as current sources connected in parallel, extending the current range of the setup. All channels are interconnected with TSP link to provide single script output control. We programmed a measurement script that enabled automated measurements up to 1 V and 9 A with the worst-case voltage measurement accuracy of \( \pm 0.035\% \) and the worst-case current measurement accuracy of \( \pm 0.18\% \) [14]. The OCVD measurement setup is based on a 16-bit PCI6014 DAQ card controlling the switch and measuring the voltage decay. Sampling frequency is set to 200 kHz with the worst-case voltage measurement accuracy of \( \pm 0.031\% \) [15].

Measurements under illumination were carried out on a temperature-controlled platform under a Newport class A continuous solar simulator. The STC conditions were met; the cell temperature regulation was maintained at 25°C by a temperature-stabilized measuring table [16], and the solar irradiance of 1000 W/m² was set using a calibrated reference solar cell with \( \pm 2\% \) accuracy [17]. Following the acquisition of the required measurements, the algorithm starts with extraction of the two-diode static model parameters \( (I_{s1}, n_1, I_{s2}, n_2, R_s, \text{and } R_{sh}) \) from the measured \( I-V \) curve. Extraction of \( R_s \) is based on a method given in [18], where further improvements are implemented to optimize the accuracy of the dynamic model. A fully automated algorithm in MATLAB is developed that comprehends the following steps.

I. The influential range for the series resistance \( R_s \), diode \( D_1 \), and diode \( D_2 \) on the input \( I-V \) curve is determined.

II. The series resistance \( R_s \) and the diode ideality factor \( n_1 \) are extracted using a bijective transformation and linear regression [18]. The inner solar cell potential \( V_d = V - R_sI \) is calculated for further parameter extraction.

III. The \( D_1 \) diode’s saturation current \( I_{s1} \) is calculated from the upper exponential region of the \( I-V \) curve. A derivative-free unconstrained simplex multivariable minimum search method is used to obtain the best fit [19] in the selected voltage range determined by the curve alignment function

\[
\theta_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} 2 \log|\frac{I_{meas}(U_i)}{I_{model}(U_i)}|}{n}} .
\]

The modelled curve is calculated at voltage points \( U_i \) of the measured curve. Index \( i \) runs through \( n \) measured points of the selected voltage range.

IV. The current of \( D_1 \) is subtracted from the total current. Both diode \( D_2 \) parameters are calculated from the lower exponential region of the remaining current using the same derivative-free unconstrained simplex multivariable minimum search method.

V. The shunt resistance \( R_{sh} \) is calculated as the derivative of the \( I-V \) curve at \( V = 0 \) and subtracted by the derivative of \( D_1 \) and \( D_2 \) characteristics [18].

VI. \( D_2 \) parameters are recalculated with a new target current. Both the \( D_1 \) and \( R_{sh} \) currents are subtracted from the total current.

VII. An additional step is added to fine-tune the diode \( D_1 \) parameters. \( I_{s1} \) and \( n_1 \) are recalculated to minimize the error in the range where the currents of both diodes are of comparable magnitudes.

Once the static parameters are known, we proceed with the extraction of the dynamic parameters \( (\tau_d \text{ for } C_{ds}, C_{j0} \text{ for } C_f) \). The effective lifetime \( \tau_d \) can be extracted from the OCVD signal using the equation [20]

\[
\tau_d = \frac{nkT}{q} \left| \frac{dV}{dt} \right| ,
\]

where \( dV/dt \) is the slope of the linear part (region ii) of the OCVD signal. In the case of solar cells, where diffusion lengths approach the length of the base, the voltage decay is influenced by the base-emitter coupling effect causing the region ii to deviate from a straight line [20]. Extraction of \( \tau_d \) from (5) is unreliable in such case. Our method uses (5) only for initial approximation of the simplex algorithm.
The initial approximation of the $C_{ji}$ parameter can be calculated form (2) considering typical semiconductor parameters of the solar cell under investigation. Higher precision of $C_{ji}$ is obtained from the low-bias region of the OCVD signal (region iii), where the exponential decay is driven only by $C_j$.

An unconstrained simplex multivariable minimum search optimization algorithm is used to minimize the error between the OCVD simulation and measurement. Best fit is obtained for both the $\tau_d$ and the $C_{ji}$ parameters at the same time. The algorithm is implemented in MATLAB, where SPICE netlist is generated, and transient analysis is executed for each optimization step. Error between the measurement and simulation is calculated and passed back to the optimization algorithm. The extraction algorithm applied to the three test cells with the basic parameters shown in Table 1 yields the extended two-diode model parameters shown in Table 2 together with the static $I-V$ RMS curve alignment factor.

2.4. Evaluation of the Extraction Method and the Extended Model. An accurate static model is required for accurate dynamic parameter extraction. However, there is no direct relation between the model and the parameter accuracies. The accuracy of the presented parameters in Table 2 is not relevant as the dynamic parameters are not calculated straightforward from the static parameters. It is the static $I-V$ curve matching that is essential for good OCVD simulation agreement. We can show good static $I-V$ curve alignment between model simulations and measurements, thus proving that such model is suitable for use over wide operating range of solar cells as seen in Figure 4. Accompanying curve alignment RMS errors defined by (4) are listed in Table 2 and range in the three cases from 0.0279 to 0.0491.

The quality of the dynamic model parameters can first be estimated by observing the degree of alignment between the simulated OCVD signal and the measured one. In the case of inaccurate dynamic (or static) model parameters, the simulated OCVD signal does not match the measured OCVD signal. Figure 5 shows a good alignment with slight deviations in the higher voltage range of mc-Si and BC mc-Si cells. Analysis showed that the deviations are a result of the base-emitter coupling effect that is not included in the dynamic model.

The minority carrier lifetimes are injection level dependent, especially when high injection levels are reached. However, in the range from 0.2 to 1, sun irradiance silicon-based solar cells are found in the low injection regime, where the lifetime does not vary significantly [21]. To verify the assumption, OCVDs of all test cells were measured at initial currents of 6 A, 4 A, and 2 A and compared to simulations using parameters extracted at short-circuit currents under STC (Table 2). The simulations were performed under equal conditions as the measurements, and the alignment is comparable to the alignment seen in Figure 5. From that, we can assume that a constant minority carrier lifetime can be used to analyse the effect of irradiance in the range from 1100 W/m² down to 200 W/m².

For the purpose of further evaluation, errors between several $I-V$ scans with varied scan speeds versus a slower transient reference scan have been compared between measurement and simulation. A simple approach to vary the scan time of the $I-V$ curve sweep from $I_{SC}$ to $V_{OC}$ is to vary the capacitance of a capacitive load. At $t = 0$, a power MOSFET connects the load capacitor to the DUT. The load capacitor starts charging with the initial current limited by the series resistance of the measurement circuitry including the series resistance of the load capacitor. To compensate the resistance and attain the short circuit current, a small negative initial charge is applied to the load capacitor prior to the measurement. During the $I-V$ curve sweep, the current and voltage of the DUT are measured using two channels of the DAQ interface.

A series of measurements and simulations were performed on the three cells. Figure 6 presents some of them for the mc-Si cell (measurement B is omitted for better readability of the chart). The load capacitor values, the scan times, and the errors of both simulations and measurements are shown in Table 3.

The agreement between measurement and simulation is within the acceptable tolerance of $\pm 0.1\%$ with an exception of measurements C and D of the BC mc-Si cell. Solar cells with diffusion lengths approaching the physical length of the base encounter the base-emitter coupling effect that decreases the accuracy of the $C_d$ model. The selected $C_d$ model causes the error of such solar cells to be overestimated. The misalignment arises at higher error values and shorter scan times, whereas at measurement B, at error value of 1.4%, the mismatch error between measurement and simulation is still within $\pm 0.1\%$.

In capacitive $I-V$ curve measurement, as well as in semiconductor/resistive measurement, the scan speed has almost no effect on $I_{SC}$. Solar cell’s dynamic error manifests in somewhat lower voltage reading on the DUT terminals. The voltage mismatch in the area near $I_{SC}$ is detectable only in low-quality cells, where the shunt resistance creates a significant current slope. In regular quality cells, even though the voltage mismatch does exist, it is undetectable due to the almost constant $I-V$ curve slope near $I_{SC}$. The $V_{OC}$ on the other hand is strongly affected in semiconductor/resistive curve tracer systems but is not affected in capacitive-based tracer systems. As the capacitor is reaching its top charge, the current rate decreases, and the transient error fades away. Therefore, we can only observe the effect of scan speed on $P_{MPP}$ shown in Table 3. As expected, the $P_{MPP}$ is hardly affected in the pc-Si cell with mild dynamic character, whereas in the BC mc-Si cell due to the expressed diffusion capacitance, the measured maximal power at the fastest scan speed is significantly reduced.

2.5. The Generalized PV Module Model. PV modules are typically constructed from single cells connected in series. An equivalent generalized model can be introduced to model the PV module $I-V$ characteristics using a small amount of circuit parameters [22]. In general, the characteristics of solar cells within a module should be as similar as possible
### Table 1: Basic parameters of solar cells under investigation under STC.

<table>
<thead>
<tr>
<th>Name</th>
<th>$A$, cm$^2$</th>
<th>$I_{SC}$, $A$</th>
<th>$V_{OC}$, $V$</th>
<th>$FF$, %</th>
<th>$P_{mpp}$, W</th>
<th>$\eta$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc-Si</td>
<td>240</td>
<td>7.46</td>
<td>0.586</td>
<td>75.3</td>
<td>3.29</td>
<td>12.9</td>
</tr>
<tr>
<td>mc-Si</td>
<td>240</td>
<td>8.59</td>
<td>0.631</td>
<td>79.5</td>
<td>4.31</td>
<td>17.9</td>
</tr>
<tr>
<td>BC mc-Si</td>
<td>153</td>
<td>5.88</td>
<td>0.660</td>
<td>76.8</td>
<td>2.98</td>
<td>19.5</td>
</tr>
</tbody>
</table>

### Table 2: Extracted model parameters of solar cells under investigation under STC.

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_s$, mΩ</th>
<th>$R_{sh}$, kΩ</th>
<th>$I_{s1}$, $\mu A$</th>
<th>$n_1$</th>
<th>$I_{s2}$, $\mu A$</th>
<th>$n_2$</th>
<th>$\tau_d$, $\mu s$</th>
<th>$C_{j0}$, $\mu F$</th>
<th>$\theta_{RMS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc-Si</td>
<td>3.41*</td>
<td>2.85</td>
<td>0.104</td>
<td>1.293</td>
<td>1.68</td>
<td>4.240</td>
<td>5.0</td>
<td>12.5</td>
<td>0.0279</td>
</tr>
<tr>
<td>mc-Si</td>
<td>0.371</td>
<td>10.4</td>
<td>0.0288</td>
<td>1.260</td>
<td>0.150</td>
<td>3.588</td>
<td>35.0</td>
<td>5.0</td>
<td>0.0287</td>
</tr>
<tr>
<td>BC mc-Si</td>
<td>2.01*</td>
<td>0.115</td>
<td>0.204</td>
<td>1.543</td>
<td>0.420</td>
<td>4.550</td>
<td>240</td>
<td>1.0</td>
<td>0.0491</td>
</tr>
</tbody>
</table>

*Measured with soldered ribbons.

### Figure 4: Alignment between modelled and measured $I-V$ curves of selected solar cells shown in semilogarithmic scale.

### Figure 5: Alignment between modelled and measured OCVD signals of selected solar cells.

### Table 3: Capacitive curve tracer $I-V$ results: measurement versus simulation.

<table>
<thead>
<tr>
<th>$C_m$, [mF]</th>
<th>Meas.</th>
<th>pc-Si</th>
<th>mc-Si</th>
<th>BC mc-Si</th>
<th>$t$, ms</th>
<th>$P_{mpp}$, W</th>
<th>$E_{meas}$, %</th>
<th>$E_{sim}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.1 ± 2%</td>
<td>Ref.</td>
<td>22.0</td>
<td>3.30</td>
<td>—</td>
<td>—</td>
<td>20.5</td>
<td>4.29</td>
<td>—</td>
</tr>
<tr>
<td>28.5 ± 2%</td>
<td>A</td>
<td>17.1</td>
<td>3.29</td>
<td>0.2*</td>
<td>0.01</td>
<td>14.8</td>
<td>4.28</td>
<td>0.14</td>
</tr>
<tr>
<td>17.7 ± 2%</td>
<td>B</td>
<td>10.4</td>
<td>3.29</td>
<td>0.2*</td>
<td>0.05</td>
<td>9.1</td>
<td>4.26</td>
<td>0.21</td>
</tr>
<tr>
<td>11.6 ± 2%</td>
<td>C</td>
<td>7.2</td>
<td>3.28</td>
<td>0.2*</td>
<td>0.9</td>
<td>6.1</td>
<td>4.23</td>
<td>0.61</td>
</tr>
<tr>
<td>5.0 ± 2%</td>
<td>D</td>
<td>3.1</td>
<td>3.26</td>
<td>0.38</td>
<td>0.31</td>
<td>2.8</td>
<td>4.16</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*s/n ratio too low for accurate error determination.
to obtain the best module efficiency; thus, the theory of the
generalized model assumes a PV module is constructed of
\( N_s \) equal cells connected in series. The generalized one-diode
static model characteristics are written as follows [22]:

\[
I_M = I_{phM} - I_S \left( e^{(q(V_M - I_S R_{shM})/N_s n k T)} - 1 \right) - \frac{1}{N_s} R_{shM} I_M . \quad (6)
\]

where indices \( M \) denote quantities referred to the module.
The generalized model equals the diode model up to the
factor of \( N_s \). The same applies if a two-diode model is used
instead.

In theory, the total module capacitance is 
\( C_{dM}(V_M) + C_{jM}(V_M) = \left( \sum_{i=1}^{N_s} (C_{di}(V) + C_{ji}(V))^{-1} \right)^{-1} \). The junction capacitance at zero voltage equals 
\( C_{j0M} = C_{j0}/N_s \) in the case of identical cells. In the case of nonidentical cells’ \( C_{j0} \), the
total \( C_{j0M} \) equals parallel connection of individual \( C_{j0} \) values.

From (3) and (6), presuming equal \( \tau_d \) of all cells, the \( C_d \)
can be expressed as

\[
C_{dM}(V_M) = \frac{q}{2N_s n k T} I_S \left( e^{(q(V_M - I_S R_{shM})/N_s n k T)} - 1 \right) \tau_d , \quad (7)
\]

in the case of a PV module. As expected, the value of the
minority carrier lifetime withholds the value of a single cell,
whereas the total capacitance reduces by the factor \( N_s \).

A test module with access to all interconnections between
the individual cells (built of 4 monocrystalline silicon SCs
shown in Figure 7) was laminated in our laboratory. Valida-
tion of the method for the dynamic parameter extraction of
a PV module is carried out through the distribution of the
dynamic components along the module. Figure 8 displays
the OCVD measurement of the individual cells, the sum of
the individual measurements, and the OCVD measurement
of the entire module.

Very good agreement between the sum and the module
OCVD response with deviation only at times \( t < 0 \) s can
be observed. This deviation arises from the series resistance
of bus bars used to contact the cell interconnections. The
actual series resistance of the module is determined from
the \( I-V \) measurement and is properly considered in the
dynamic parameter extraction method. The OCVD signal of
the module equals the sum of the individual responses of SCs
involved; therefore, in the OCVD signal of the PV module
each solar cell contributes its share of charge proportional
to its total internal capacitance. The OCVD signal of the PV
module can thus be used to extract \( C_{j0M} \) and \( \tau_{dM} \) parameters,
where \( C_{j0M} \) should equal the parallel connection of the
individual \( C_{j0} \) values, and \( \tau_{dM} \) should equal the average value
of the individual \( \tau_d \) values. The individual values of \( C_{j0M} \)
and \( \tau_{dM} \), however, should not diverge considerably from each
other.

Table 4 displays results of the parameter extraction
method applied to the individual cells and to the module.
Most results calculated from individual cells are in good
agreement with the theory. The discrepancy in the \( R_s \)
can be explained through the resistance of additional bus bar
length required to contact individual cells. The second
discrepancy, found in \( I_{S2} \), is caused by cell 4 with parameter
\( I_{S2} \) unfortunately significantly smaller compared to the other
cells. In such case, the effective $I_s$ is not determined by the smallest $I_s$ value.

However, the extracted dynamic parameters are determined within the expected range of tolerance, and extraction process can be used to determine the generalized two-diode model for PV modules when cells with similar properties are involved, which is the case in all high-efficiency PV modules.

3. Scan Time Determination

The minimum scan time of a single cell or a PV module at a predefined error threshold can be determined by an iterative algorithm from a series of transient $I$-$V$ curve simulations. The dynamic model of the DUT is used for both the reference and the compared curve simulations. The reference curve is simulated by sweeping the operating point (OP) analysis to eliminate the capacitance effects, whereas the compared curves are simulated using transient analysis. The numerical computation and netlist generations are handled in MATLAB, whereas SPICE is executed within MATLAB for circuit simulations (Figure 9).

In the process of determination of the maximal tolerable predefined error threshold, other sources of $I$-$V$ curve errors as well as the ratio of the required scan time to the $I$-$V$ curve error should be considered. It is reported that specialized laboratories are able to achieve $I$-$V$ curve measurement uncertainties from 1.6% to 3% [3]. Also in Figure 10, we can observe a quasieponential decrease of error versus scan time leading to very long scan times at low error thresholds. Determination of the predefined error depends strongly on the purpose of the measurement. To stay at least a factor of 3 below other uncertainties and to avoid too long scan times (Figure 10), the predefined error threshold was set at 0.5%. Rendered optimum scan times are 2.2 ms, 7.3 ms, and 43.8 ms for the pc-Si, mc-Si, and BC mc-Si solar cells, respectively.

4. Effect of Irradiance Level

4.1. Experiment Background and Expectations. In the study of the influence of irradiance ($G$) on the scan time, the RC time constant $\tau_c$, causing the delay when sweeping the $I$-$V$ curve from point to point, should be calculated. In forward bias, the $C_d$ dominates the total cell capacitance, and the current through the $D_2$ is negligible. When sweeping the $I$-$V$ curve using a voltage source, the time constant is defined as

$$\tau_c = RC = \frac{C_d}{g_s + g_{sh} + g_d}, \quad (8)$$

where $g_s = 1/R_s$, $g_{sh} = 1/R_{sh}$, and $g_d$ is differential conductance of the diode $D_1$ between the neighbouring points. The following equation can be derived using simplified equations for $C_d$ and $g_d$ [10] and assuming that $g_{sh} \ll g_s$:

$$\tau_c = \frac{\tau_d}{2} \left( \frac{I_{di}}{g_s V_T} \right). \quad (9)$$

$I_{di}$ is the current flowing through the diode $D_1$ (Figure 3), and $V_T$ is the thermal voltage. Equation (9) implies that the time constant is slightly increasing with diode current. The current $I_{di}$ is the difference between the photogenerated current and the current flow out of the device terminals ($I_{di} = I_{ph} - 1$). At $V_{OC}$, where $I = 0$, the decrease in irradiance yields lower time constants and thus smaller transient errors.

The trend of $\tau_c$ can be observed in a step response of the measured device. A simulation in $V_{OC}$, where the time constant is maximal, with a step amplitude of 0.01 V, has been performed at different currents $I_{di}$. A sweep of $I_{di}$ is used to model the change in irradiance. The stationary $V_{OC}$ conditions have been established by a large capacitor in series with a step voltage source.

Simulation in Figure 11 confirms the (9). A decrease in irradiance yields shorter step responses and shorter time
Table 4: Extracted parameters of individual cells and module (monocrystalline silicon solar cells).

<table>
<thead>
<tr>
<th>Cell</th>
<th>$R_s$, mΩ</th>
<th>$R_p$, kΩ</th>
<th>$I_{ph_1}$, μA</th>
<th>$n_1$</th>
<th>$I_{ph_2}$, μA</th>
<th>$n_2$</th>
<th>$\tau_d$, μs</th>
<th>$C_{0s}$, μF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>6.251</td>
<td>5.0</td>
<td>5.65</td>
<td>1.15879</td>
<td>141.0</td>
<td>35.0</td>
<td>4.50</td>
<td></td>
</tr>
<tr>
<td>Cell 2</td>
<td>9.693</td>
<td>1.2</td>
<td>5.77</td>
<td>1.16285</td>
<td>446.0</td>
<td>45.0</td>
<td>5.70</td>
<td></td>
</tr>
<tr>
<td>Cell 3</td>
<td>7.086</td>
<td>5.0</td>
<td>3.80</td>
<td>1.13891</td>
<td>696.0</td>
<td>45.0</td>
<td>5.30</td>
<td></td>
</tr>
<tr>
<td>Cell 4</td>
<td>10.216</td>
<td>6.3</td>
<td>5.15</td>
<td>1.15259</td>
<td>33.9</td>
<td>45.0</td>
<td>4.70</td>
<td></td>
</tr>
<tr>
<td>Module calculated</td>
<td>33.246</td>
<td>17.5</td>
<td>3.80</td>
<td>4.61314</td>
<td>33.9</td>
<td>42.5</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Module measured</td>
<td>23.039</td>
<td>17.0</td>
<td>3.49</td>
<td>4.53281</td>
<td>183.0</td>
<td>41.3</td>
<td>1.43</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11: Simulated step response of mc-Si solar cell.

4.2. Effect of Irradiance on I-V Curve Error. The source of the transient error is the capacitance that introduces the time constant $\tau_C$. As soon as the capacitance is present in the circuit, there are several factors aside the time constant affecting the magnitude of the error.

(i) The duration of I-V scan severely impacts the error: each time the load changes, the capacitor charge needs to be equalized. The transient error directly depends on $dV/dt$ between consequent scan points. When the same sweep algorithm is involved, what matters is the total time to sweep from $I_{SC}$ to $V_{OC}$, regardless of the number of points.

(ii) The I-V curve sweep algorithm: achieving a homogenous density of I-V curve points is a common issue. Constant current (or voltage) step yields approximately equidistant point distribution from the maximum power point to $V_{OC}$ (or to $I_{SC}$) and only a few points in the other direction. Different approaches are used to acquire equidistant point distribution along the curve such as logarithmic voltage step, combined voltage and current stepping, adaptable on the fly step calculation. Whichever method is used, they all vary $dV/dt$ throughout the I-V curve.

(iii) Lastly, the method of error determination also affects the I-V curve error: strictly considering the time constant, both points being compared should be selected at the same time of the measurement. However, the I-V curve does not contain the time information and has to be compared according to the equal power availability. Furthermore the direct comparison of two curves at different irradiance is impossible due the modified $I_{SC}$, the $V_{OC}$, and the entire curve path.

The error is thus determined using the method from Section 2 between a transient simulation and a quasi static operating point analysis (the ideal reference I-V curve).

The scan time for each DUT is determined from the predefined error threshold of 0.5% at STC. The variation of irradiance in simulations is modelled through variation of the photogenerated current $I_{ph}$.

The I-V curve error versus irradiance for all three cells under test (Figure 12) surprisingly yields a result of reversed error/irradiance dependency. The sweep is performed at a high-density constant voltage step rate to exclude the

Figure 12: Effect of irradiance variation on transient error.
error arising from this source. Although the time constant decreases with decreasing irradiance, the error and consequently the optimal scan time moderately increase. The reverse trend arises from calculation of the relative error value. The effects of $V$ and $I$ can be evaluated separately. First, we focus on the relative current error calculation. At decreasing irradiance, the absolute error of current ($\delta I$) slightly decreases due to the fall of $\tau_C$ (9). For calculation of the relative error, the $\delta I$ is divided by the short circuit current $I_{SC}$, which also decreases with the irradiance. Assuming, $I_{ph} \approx I_{SC}$, the reduction of $I_{SC}$ is more rapid than the reduction of $\delta I$, which is proportional to the $\tau_C$. Consequently, the overall error increases although the time constant decreases with irradiance. The actual error defined in (1) is an aggregate of the relative current error and the relative voltage error. The open circuit voltage varies only minor in observed irradiance range; thus, the trend of error versus irradiance mostly reflects the trend of relative current versus irradiance. As the desired output of an error function is certainly a relative value of the $I-V$ curve error, a moderate increase of error at lower irradiance levels should be considered at scan time determination procedure, in particular at outdoor monitoring sites. In scope of the three tested cells of different silicon technologies, the maximum relative deviation of error was 32% for the polycrystalline silicon solar cell at irradiance level of 200 W/m$^2$ compared to 1100 W/m$^2$.

5. Conclusions

A method of optimal $I-V$ curve scan time determination of solar cells and modules based on the extended two-diode model was presented. An algorithm acquiring the parameters of the presented model from two simple measurements, an $I-V$ scan and an OCVD signal, has been introduced. A newly introduced error determination function is used to estimate the mismatch between two $I-V$ curves. Different aspects on determination of the tolerable predefined $I-V$ curve error threshold caused by the PV generator’s dynamic character were analysed. The predefined error threshold served as a base for the optimal scan time determination. The proposed extraction method has been applied but is not limited to different wafer-based solar cells and modules. Validation was achieved using capacitor-based $I-V$ curve measurement, where different scan times were accomplished by variation of the load capacitance. The extraction method gives good results, whereas there is still some space for dynamic model improvement (PV generators with high minority carrier lifetimes). $I-V$ curve error versus scan time dependency has been analysed where at error threshold of 0.5% scan times diverge from 2.2 ms up to 43.8 ms for DUTs of different silicon solar cell technologies. Therefore, the capacitive character of a DUT should certainly be considered prior to $I-V$ curve measurement.

Even though the capacitance and the time constant of PV generators decrease with decreased irradiance, an increase of the error was ascertained. Mostly due to the relative current error, a moderate relative increase of 32% above the predefined 0.5% error threshold for the poly-crystalline solar cell under test was determined. When very high-precision measurements are required, such increase of error can affect the final measurement. The scan time should either be determined at the lowest expected irradiance level or a sufficient threshold error tolerance should be considered at the highest level of irradiance.

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References


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