Minimizing measurement uncertainties: Challenges for power measurement of high-efficiency c-Si PV modules

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ABSTRACT

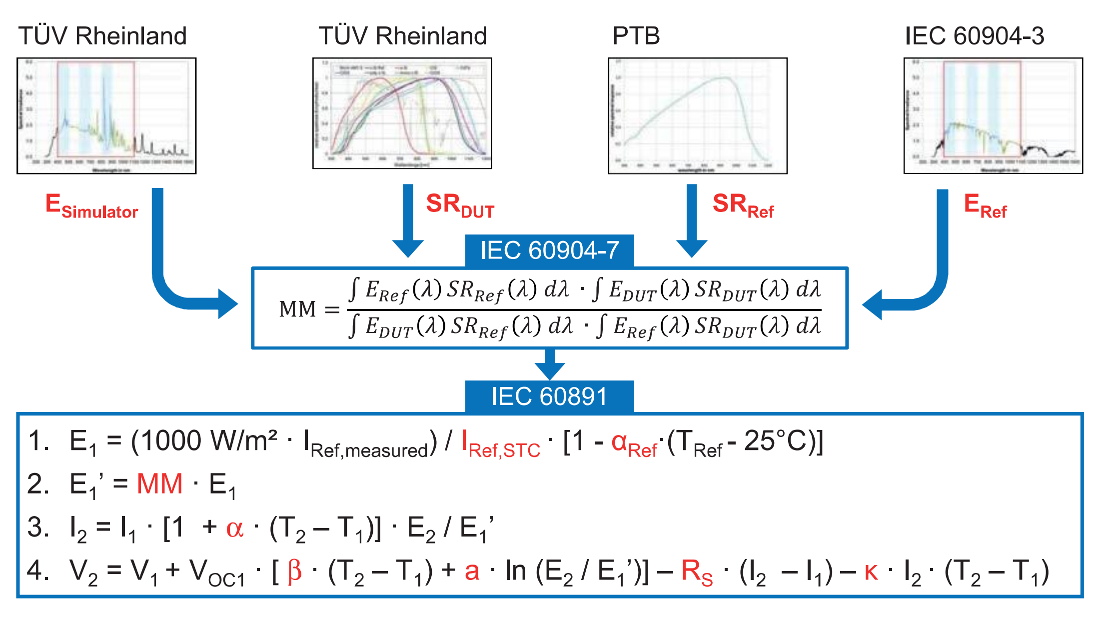
High-efficiency (HE) PV technologies, such as heterojunction, back-contact or n-type, can be affected by significant measurement errors compared with conventional technologies; the power measurement of HE crystalline silicon PV modules and cells has therefore been a challenge for the PV industry for at least two decades. To deal with the internal capacitance and the spectral mismatch errors of HE cells and modules, various measurement techniques are currently used: steady-state, multi-flash, dynamic *I–V*, DragonBack™ and dark *I–V* and reconstruction methods, to name a few. This paper discusses the challenges and provides guidance for best practice for acquiring accurate measurements.

Introduction

There are a number of cell concepts on the market that achieve high module efficiencies of 20% or more; among these are selective emitter p-type cells, n-type cells, back-contact solar cells, such as MWT (metallization wrap-through) or IBC (interdigitated back-contact), and heterojunction cells. Most of these cell concepts work with a reduced metallization on the front side to avoid shading effects. While, for example, the IBC concept has both p and n polarities and the junction located on the rear of the device, the MWT concept has both polarities on the rear and the junction on the front of the device.

As a result of increased efficiency and material purity, the module capacitance and carrier lifetime/diffusion lengths have increased. The consequence of the increase in carrier lifetime/diffusion lengths is that the charge carriers of high-efficiency (HE) c-Si PV modules travel longer distances, and thus the PV module becomes spectrally more sensitive in the infrared wavelength range. The high capacitance effect increases with higher voltages; this, together with the improved spectral behaviour, presents challenges for measuring the power of the modules/cells.

> "A crucial challenge for the measurement of HE c-Si PV modules is the spectral mismatch."



$$MM = \frac{\int E_{Ref}(\lambda)\, SR_{Ref}(\lambda)\, d\lambda \cdot \int E_{DUT}(\lambda)\, SR_{DUT}(\lambda)\, d\lambda}{\int E_{DUT}(\lambda)\, SR_{Ref}(\lambda)\, d\lambda \cdot \int E_{Ref}(\lambda)\, SR_{DUT}(\lambda)\, d\lambda}$$

1. $E_1 = (1000\ W/m^2 \cdot I_{Ref,measured}) / I_{Ref,STC} \cdot [1 - \alpha_{Ref} \cdot (T_{Ref} - 25°C)]$
2. $E_1' = MM \cdot E_1$
3. $I_2 = I_1 \cdot [1 + \alpha \cdot (T_2 - T_1)] \cdot E_2 / E_1'$
4. $V_2 = V_1 + V_{OC1} \cdot [\beta \cdot (T_2 - T_1) + a \cdot \ln(E_2 / E_1')] - R_S \cdot (I_2 - I_1) - \kappa \cdot I_2 \cdot (T_2 - T_1)$

Figure 1. Spectral mismatch and *I–V* curve correction.

Challenges for power measurement

Spectral mismatch

A crucial challenge for the measurement of HE c-Si PV modules is the spectral mismatch, because, compared with standard c-Si PV modules, HE cells have very different relative spectral responses and a significantly higher collection of responses at high wavelengths. The uncorrected spectral mismatch may therefore result in additional measurement errors, potentially exceeding 2%, even for solar simulators with an IEC 60904-9:2007 spectral match A-classification. Because of this, TÜV Rheinland recommends spectral mismatch corrections using a spectral mismatch factor for HE PV modules in particular [1].

The spectral mismatch factor is a correction factor for the irradiance of the solar simulator; it is measured using a calibrated reference device and determined in accordance with IEC 60904-7:2008. The effective irradiance administered to the test module is increased or decreased accordingly to match its output under standard test conditions (STC). The spectral mismatch factor is used to correct the difference between the reference spectral irradiance in accordance with IEC 60904-3:2008 and the measured solar simulator's spectral irradiance in combination with different relative spectral responses of the reference device and the tested PV module [2]. The *I–V* curve correction is performed in conjunction with the irradiance and temperature correction in accordance with IEC 60891:2008 (Fig. 1).

In the case of spectral match class A solar simulators, the correction of spectral mismatch can reduce the error contribution to less than 0.4% and significantly improve the accuracy of the performance measurement.

Internal capacitance

The total capacitance of a solar cell consists of the junction, diffusion and transition-carrier capacitances. Junction capacitance, which represents the charge storage in the depletion layer, dominates the cell capacitance in reverse-bias and low forward-bias conditions. Diffusion capacitance corresponds to minority-carrier storage in the quasi-neutral regions of the junction, and becomes significant in forward bias. Transient-carrier capacitance is attributed to the existence of defect and interface states. Diffusion and transient-carrier capacitance have an exponential dependence on the applied voltage; this allows the two to be combined into the free-carrier capacitance [3].

HE c-Si modules are usually highly capacitive, and power measurements can be influenced by sweep-time effects when the *I–V* curve scan acquisition times are too fast [4]; as a result, measurement techniques are affected and errors occur. To ensure the power measurement's validity, sweep-time effects can be identified by performing a sweep in both directions, from short-circuit current to open-circuit voltage, and vice versa. The capacitive characteristics depend on the specific technology, and for calibration purposes the appropriate *I–V* curve sweep speed needs to be established experimentally.

One solution is to extend the duration of light exposure; however, a longer light exposure can increase the temperature of the cell or module, which can distort the *I–V* curve. In addition, the light source has to remain stable for a longer duration, the lifetime of the solar simulator light bulbs is reduced, and the throughput will slow down. To increase the yields and the throughput at the same time, TÜV Rheinland has developed a novel measurement technique: the so-called dynamic *I–V* method, which will be discussed later.

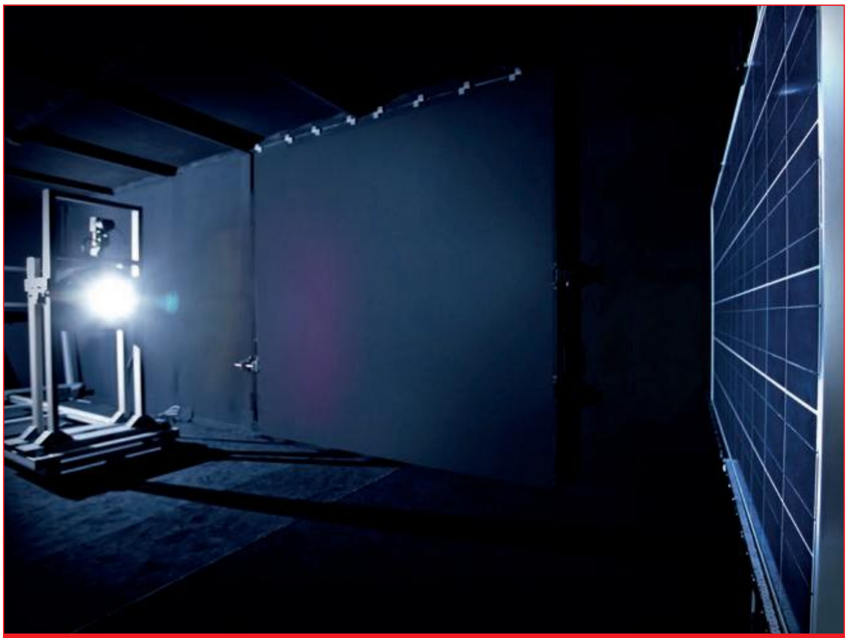


Figure 2. TÜV Rheinland pulsed solar simulator.

Figure 3. TÜV Rheinland steady-state solar simulator.

Power measurement techniques

Solar simulators enable the PV industry and testing laboratories to reproducibly determine the *I–V* characteristics of PV devices. In most cases, an indoor pulsed solar simulator (Fig. 2) is used, which delivers *I–V* curves that define the electronic performance of the tested devices. A pulsed solar simulator has the advantage that test conditions, such as temperature or irradiance, can be easily adjusted, thus achieving a high level of reproducibility. Moreover, the tests can be performed independently of changeable outdoor weather conditions.

By adjusting certain parameters, solar simulators can be used in a very accurate way, and uncertainties caused by irradiance and temperature correction can be kept low. Nevertheless, the high capacitance of HE c-Si PV modules complicates the module characterization, because HE c-Si modules often require flash durations that are longer than those achievable by most of the common solar simulators on the market. In spite of this, solutions do exist for measuring the power of a HE c-Si device – for example steady-state, multi-flash and single-flash techniques, among others.

Steady-state measurement

Steady-state solar simulators (Fig. 3) can handle sweep-time effects, because they can be operated with individually adjusted *I–V* curve acquisition times, and with no dependency on the light duration of the optical system. Once the measurement parameter has been adjusted, these simulators usually have a high throughput, and are able to deliver reliable results. The equipment is expensive, however, and maintenance costs are also high (e.g. frequent checks for non-uniformity of light and spectrum, caused by bulb ageing); additionally, the high energy consumption of the system increases the cost per measurement.

The steady-state measurement technique requires a high level of experience and well-trained operators. The temperature, for example, has to be monitored frequently, and in most cases has to be corrected. Even so, temperature non-uniformities over the module area, and positive and negative temperature gradients, can cause errors. Fig. 4 compares measurement results from pulsed and steady-state simulators.

Point-by-point measurement

A rarely used method is the point-by-point *I–V* curve measurement (Fig.

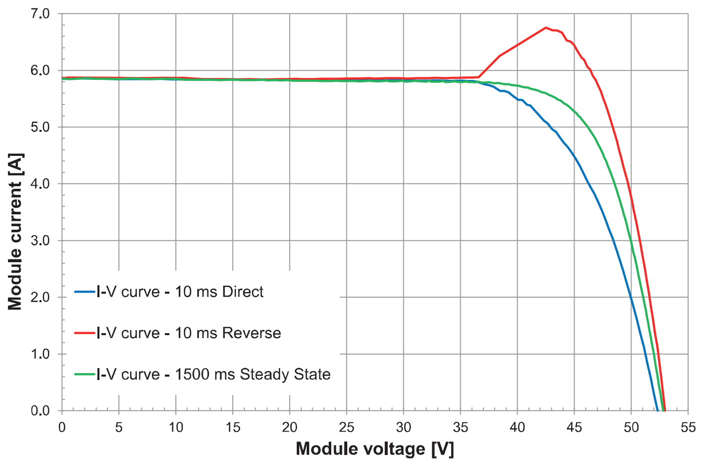


Figure 4. Comparison of measurement results with pulsed and steady-state solar simulators.

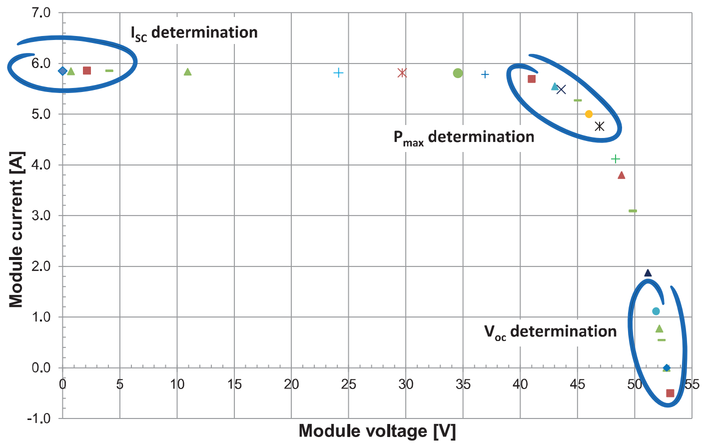


Figure 5. Illustration of the point-by-point measurement method.

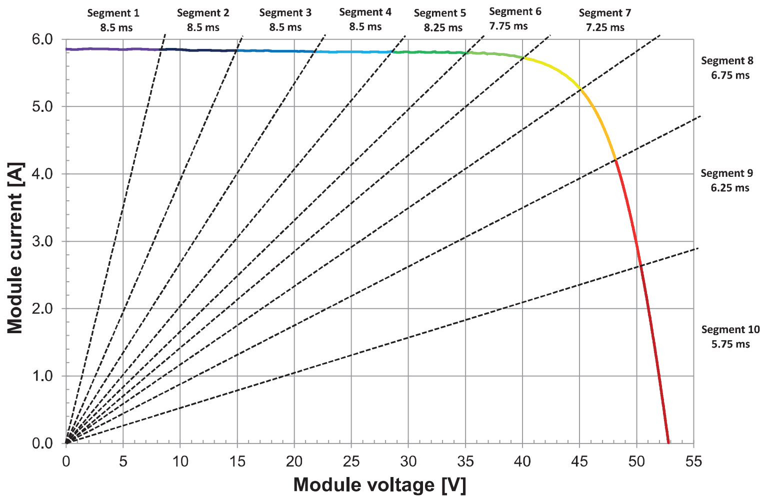


Figure 6. Sequential *I–V* curve measurement using the split-flash method (10 flashes).

5): here, the voltage is kept constant during each single light pulse, and the particular *I–V* data (irradiance, voltage and current) are determined at single working points in the three most important *I–V* curve regions of I_{sc}, V_{oc} and P_{max}. The entire *I–V* curve is then created using these single data points in conjunction with a mathematical interpolation of intervals. The advantage is that the working points can be measured using practically the entire light-pulse duration.

Point-by-point power measurement can be a possible solution for HE c-Si PV modules. The advantage of this measurement technique is that the temperature requires only slight correction, and the device being tested can be prepared more easily with regard to temperature. On the other hand, point-by-point measurement techniques take significantly longer, and between 15 and 20 flashes are necessary in order to achieve reliable results.

Multi-flash *I–V* curve measurement

Another power measurement procedure for PV modules with low to medium-high capacitance is the multi-flash, or so-called 'split-flash', method. Its process and outcome are similar to those of the point-by-point measurement, but with the difference that the *I–V* curve is measured continuously, avoiding gaps in the data acquisition; it therefore does not rely on subsequent curve fitting. During the measurement, the *I–V* curve is divided into several segments, which are measured consecutively using the corresponding number of flashes for different subsections (Fig. 6).

This method delivers accurate results, especially for low- and medium-capacitance PV modules, when a reasonable number of flashes are used. However, it is not so reliable in the case of HE PV modules, for which a disproportionately large number of subsections need to be investigated in order to obtain reliable data. For example, the hysteresis (difference between the direct and reverse measurements) of very high capacitance heterojunction PV modules remains at 2%, even if 50 split flashes are used.

To sum up, this procedure requires not only proper documentation but also a great deal of experience in the tuning order and position of every single subsection. In addition, the use of multi-flash pulsed solar simulators for the power measurement of high-

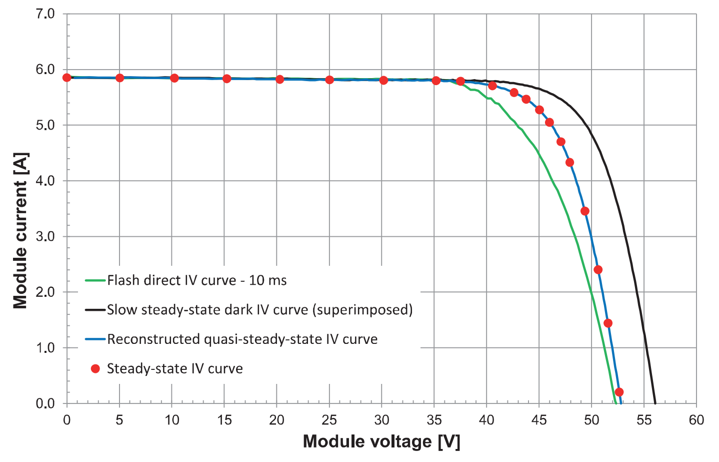


Figure 7. Functional principle of the slow dark *I–V* and reconstruction method.

TÜV Rheinland Shanghai

Measurement method: dynamic *I–V*

Test dates: 14.06.2013 onwards

Total number of projects: 28

Total number of HE modules: 61

Measurement method: multi-flash or steady-state

Total number of projects: 14

Total number of HE modules: 140

TÜV Rheinland Cologne

Measurement method: DragonBack

Test dates: 20.01.2015 onwards

Total number of projects: 5

Total number of HE modules: 16

Total number of PV modules with low-capacitance effects: 171

Measurement method: multi-flash

Test dates: 2013 onwards

Total number of projects: 70

Total number of HE modules: 264

Total number of PV modules with low-capacitance effects: 298

TÜV Rheinland Shanghai/Cologne Test Report Uncertainty

Measurement uncertainty on I_{sc}: 2.4%, k = 2

Measurement uncertainty on P_{max}: 2.5%, k = 2

Measurement uncertainty on V_{oc}: 0.7%, k = 2

Table 1. Measurement statistics.

capacitance modules is very time-consuming and should be restricted to low-capacitance modules.

> “The use of multi-flash pulsed solar simulators for the power measurement of high-capacitance modules is very time-consuming and should be restricted to low-capacitance modules.”

Dark *I–V* and reconstruction

A method for measuring the *I–V* curve of c-Si high-capacitance PV modules that delivers accurate results has been suggested by Virtuani and Rigamonti [5] at the University of Applied Sciences and Arts of Southern Switzerland (SUPSI). This method relies on obtaining the dark *I–V* of the PV module and its short-circuit current under illumination; the complete *I–V* curve under illumination is then reconstructed by combining this information (Fig. 7). The technique is sensitive to the effect of certain factors, such as the series resistance, on the accuracy of correction. Results presented at EU PVSEC in 2013 [6] were excellent, with errors of < 0.5% in the estimation of P_{max} for one set of technologies (HJT); satisfactory results were also obtained for another set of devices (BCT), where an overestimation of P_{max} by less than 2.5% was achieved.

To achieve reliable results, this method requires that the module's dark and illuminated currents and voltages have a similar reverse saturation current. While the throughput is high, this method demands time and experience.

Dynamic *I–V* and DragonBack methods

The dynamic *I–V* method is a single-flash measurement technique that delivers reliable results for every kind of cell and module technology with a low- to high-capacitance behaviour. This novel technique was developed by the TÜV Rheinland Research and Development team [4], and TÜV Rheinland has been using it since 2013 (see Table 1).

In the dynamic *I–V* method the quasi-steady-state *I–V* curve is sampled by maintaining the voltage constant while the current stabilizes to its capacitance-free response (Fig. 8); the final *I–V* curve measurement accurately and rapidly predicts the actual *I–V* characteristic of the test device. This method allows the electrical characterization of HE devices and yields high measurement quality. The throughput is also high, but the technique is more complicated if *I–V* corrections have to be applied.

Another procedure for measuring HE PV modules is the DragonBack method (Fig. 9), developed by SUPSI-ISAAC and Pasan SA; this method allows the *I–V* characterization of low- to high-capacitance modules without suffering from measurement artefacts. The advantage of this technique is that the *I–V* curve of low-capacitance modules can be measured within one 10ms flash; in addition, it is not necessary to determine the requisite sweep time for the measurement. For medium- and high-capacitance PV modules, however, the procedure is modified to combine standard and split-flash measurements, with up to 10 flashes. TÜV Rheinland also worked with this method in January 2015 (see Table 1).

The DragonBack method is as quick as the dynamic *I–V* method for low-capacitance modules, such as those fabricated with selective emitter p-type cells. Both of these concepts use a selected number of points of the *I–V* curve and rely on interpolation. The achievable throughput is therefore high, which makes dynamic *I–V* and DragonBack promising measurement techniques, especially for HE c-Si modules with high capacitance. The use of these methods, however, requires a great deal of experience.

Conclusion

Measuring the power of HE solar cells is a challenging task that requires specific know-how. The R&D teams of TÜV Rheinland in Cologne and Shanghai have developed several measurement techniques for handling modules with high capacitance and for measuring them precisely. TÜV Rheinland suggests the multi-flash method with a continuous *I–V* curve for modules with lower capacitances,

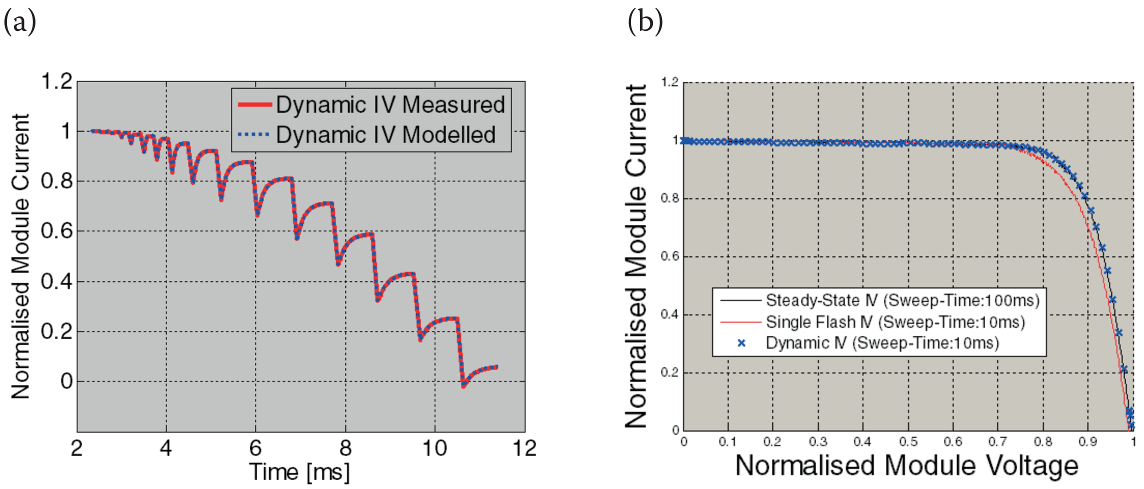


Figure 8. (a) Dynamic *I–V* method with non-linear voltage ramp and stabilized module current. (b) Perfect match of steady-state and dynamic *I–V* characteristics.

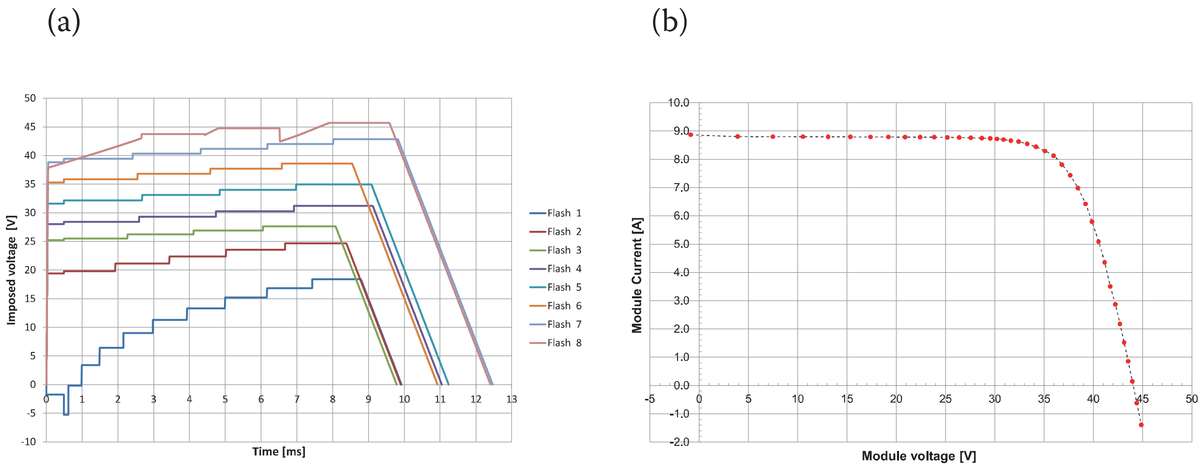


Figure 9. (a) DragonBack method with discontinuous sweep voltage for the measurement of the *I–V* curve within eight single flashes. (b) The resulting *I–V* characteristics created with interpolated data points.

such as selective emitter p-type. The dynamic *I–V* and DragonBack methods are recommended for measuring higher-capacitance PV modules.

> “The dynamic *I–V* and DragonBack methods are recommended for measuring higher-capacitance PV modules.”

With the use of these techniques, TÜV Rheinland has been able to achieve both high measurement throughputs and accurate measurements at the same time. Last, but not least, spectral mismatch corrections in accordance with IEC 60904-7:2008 are strongly advised, especially for HE PV modules, in order to further reduce measurement uncertainties.

References

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