Correction Procedures for the Flasher Calibration of PV Devices Resulting in Reduced Restrictions and Uncertainties

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ABSTRACT: Photovoltaic modules are often calibrated with the aid of pulsed solar simulators (flashers), because they achieve the needed uniformity and better spectral match without noticeable increase of module temperature. However, the I-V characteristics of both a-Si cells and high efficiency crystalline solar cells are often distorted. To explain the observed splitting of the characteristics, a macroscopic model is set up, which describes all significant effects of the distortion of the characteristics of crystalline cells. Whereas a procedure for the correction of high efficiency solar cell characteristics has already been presented in [1], in this paper different methods are compared and a correction method for a-Si cells is presented. In addition, it is shown how the spectral mismatch can be reduced by utilizing the results of a set of differently filtered flasher calibrations without measuring the spectral responsivity of the PV module.

Keywords: Calibration, Performance, Qualification and Testing

1. INTRODUCTION

Flashers have many advantages in comparison with steady-state solar simulators. Firstly, they meet the uniformity and spectral-match requirements for large area class A or B simulators more easily than steady-state simulators. Secondly, due to the short time of measurement, heating of the cell is negligible and due to the small heating effects, filter may be applied more easily to modify the simulator spectrum. Thirdly, it is much more economical to use flashers. Because of these benefits, pulsed solar simulators are widely used in quality assurance and performance tests of photovoltaic modules. In addition, spectral mismatch errors of solar simulators can be corrected much more easily in case of pulsed than in case of steady-state irradiation (see section 5).

However, the use of pulsed solar simulators requires the measurement of transient I-V characteristics within milliseconds which induces errors [1] to [4], in case of a-Si solar cells and high-efficiency / BSF solar
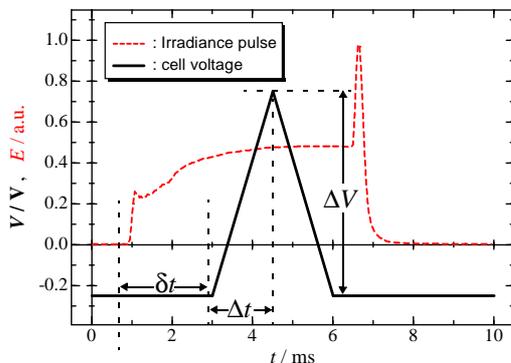
cells with very large effective diffusion lengths due to an additional current through a diffusion capacity proportional to $\exp(V/V_T)$ [5]. Whereas a correction procedure for crystalline solar cells and PV modules which is not applicable to a-Si cells has already been described in [1], in this paper the above-mentioned method is compared with other procedures, especially with a new correction method for a-Si cells [2].

2. EXPERIMENTAL ANALYSIS

A function generator, which is triggered by the onset of the radiation pulse measured by a monitor photodiode, produces the ramp voltage at the cell. Trigger delay, voltage sweep rate $\Delta V/\Delta t$, bias voltage and waveform can be varied (Fig. 1, [1]) In addition to the flasher a chopped steady-state radiation source is used, too.
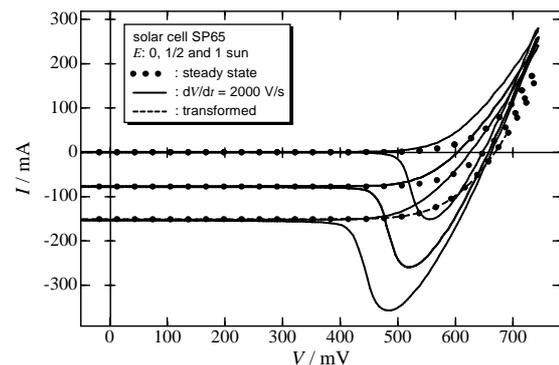
Figure 2: Examples of characteristics with a very large distortion (c Si with BSF). The maximum time of measurement Δt of 1 ms to 5 ms requires a high rate of voltage rise dV/dt, because the characteristics must be measured completely within a radiation pulse. The diffusion capacity proportional to $\exp(V/V_T)$ of crystalline silicon solar cells with BSF and/or with large effective diffusion lengths is extremely large. The additional current due to this capacity induces the distortion.

Figure 1: Irradiance pulse of a single-flash solar simulator with adjustable pulse duration and amplitude as well as cell voltage of the ramp generator as a function of time; prior irradiation is determined by adjustable time delay δt; voltage sweep rate $\Delta V/\Delta t$, bias voltage and waveform can be varied.

3. CORRECTION PROCEDURES FOR I-V CHARACTERISTICS

Different correction procedures were tested and compared. The advantages and disadvantages of these correction procedures are described in this section.

Translation (Shifting) Algorithm

Based on the measurement of the transient characteristic at one-sun irradiance level and two auxiliary measurements in the dark (transient characteristics under the same conditions and steady-state characteristics), it is possible to transform the steady-state dark characteristic by a well-defined shift of current and voltage into the required steady-state characteristic at one-sun irradiance level [1]. This procedure (Fig. 3) is most suitable for all crystalline solar cells, in particular for high-efficiency, high-resistivity silicon cells (Fig. 2) which show a strong distortion of the characteristics due to back surface fields and large effective diffusion lengths [1]. This algorithm, however, cannot be applied to the correction of the transient characteristics of a-Si cells or CIS cells, because their dark characteristics cannot simply be shifted into their characteristics under irradiance.

Measurement Point-by-Point, Multi-Flash Procedure

This procedure needs a separate flash for every pair of values (V, I) of the characteristics. During the time for the determination of one point, the voltage have to be kept constant. This multi-flash procedure [6] is the only one which can, in principle, be used for all types of solar cells; however, it is extremely time-consuming and expensive.

Measurement by Sections

The measurement by sections is a modification of the single flash method. Instead of measuring the characteristics point-by-point, small sections of the characteristics are measured, i.e. the voltage is slightly varied during the flash applying the respective bias voltage. When varying the voltage slightly, the sweep rate can be kept slow enough such that no or only small distortions are induced. If the approximate position of the maximum-power-point (MPP) is known, this procedure can be combined with the next two procedures for all types of solar cells in order to determine the maximum power point and the open-circuit voltage accurately enough.

Mean Value Formation

For this evaluation procedure with little experimental and computational effort, the characteristics must be measured at the same irradiance level; one with positive and one with negative sweep rate. The two measurements can be carried out during one single flash. Calculating the average value is meaningful only for cell types which cause a symmetrical splitting between the steady-state and the forward and reverse transient characteristics, induced by a voltage-inde-
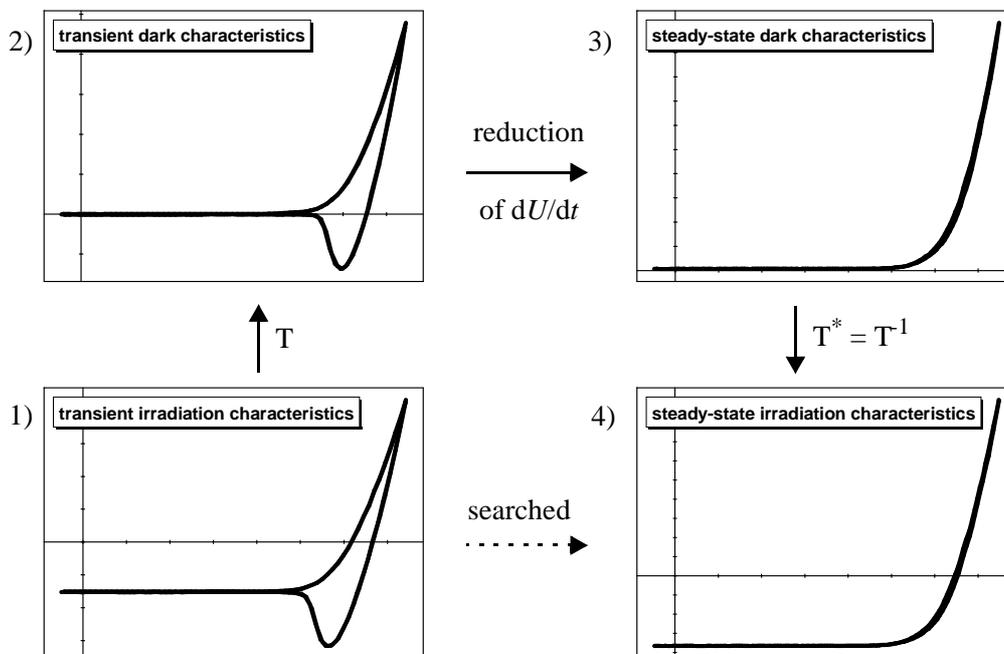

Figure 3: Illustration of the translation algorithm.
Characteristics 1), 2) and 3) are measured
4) is obtained from 3) by transformation (translation).
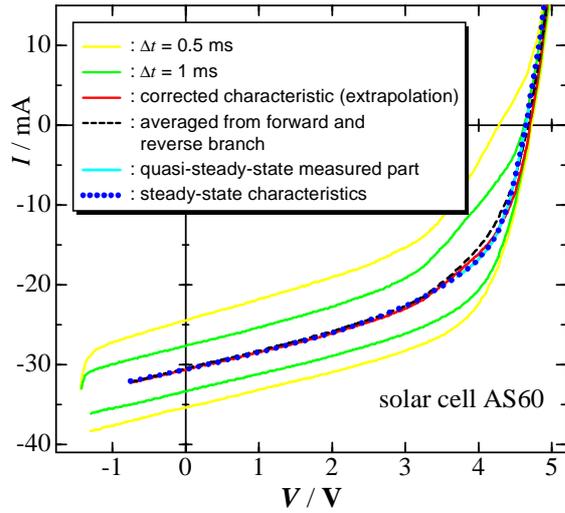The transformation parameters are determined from the 1) to 2) translation.

Figure 4: Comparison of three correction methods. (AS60 is an a-Si mini module).

pendent capacity. In case of multi-crystalline silicon solar cells and solar cells of amorphous silicon, this condition is met in practice. This procedure cannot be applied to solar cells with asymmetrical splitting (to mono-crystalline solar cells with BSF and large diffusion lengths and thus with voltage-dependent capacity as in Fig. 2 or to PIN-PIN stack cells, e.g., solar cell AS60 in Fig. 4).

Linear Extrapolation

This correction procedure makes use of the fact that the splitting of an a-Si I-V characteristic increases linearly with frequency by first approximation, i.e., the splitting doubles after doubling the voltage sweep rate or halving the time of measurement Δt. Thus, the steady-state characteristics can be calculated approximately from two transient characteristics at the same irradiance level. The splitting may be asymmetrical, however, it should not be too large since, otherwise, errors arise due to the neglection of the higher orders (see e.g. AS60). To apply this procedure after measuring a splitted transient characteristics during a flash within Δt, one has to measure the characteristic again during a second flash within $\Delta t / 2$. The difference between the first and the second measurement results must be subtracted from the first data. By first approximation, the final result represents the steady state I-V characteristics (Fig. 4).

4. SIMULATING THE DISTORTION OF THE CHARACTERISTICS

According to the equivalent circuit diagram (Fig. 5), the voltage $V^*(t)$ actually available between the points A and B produces a current for each components connected in parallel:

$$I = I_{\text{Diode}}(t) + I_{C_{\text{Diff}}}(t) + I_{R_{\text{P}}}(t) - I_{\text{Ph}}$$

$$= I_{\text{sat}}(\exp(k_0(V)^*(t)) - 1) + \frac{V^*(t)}{R_{\text{P}}} - I_{\text{Ph}}$$

$$+ C_0\left(1 + \frac{V^*(t)}{V_c}\right)V^{'*}(t)\exp\left(\frac{V^*(t)}{V_c}\right)$$

with $V^*(t) = V(t) - R_{\text{S}}I(t) - L\dfrac{dI(t)}{dt}$ and with the

approach $C_{\text{Diff}}(V) = C_0\exp(V/V_c)$ for the diffusion capacitance. Numerically solving the implicit differential equation for *I*, the characteristics shown in Fig. 6 are obtained.

5. CORRECTION PROCEDURE FOR SPECTRAL MISMATCH

For the calibration of terrestial solar cells, simulator radiation which spectrally matches the AM1.5 reference spectrum is required. Otherwise, errors of more than 10% can be observed. In order to take spectral mismatch of solar simulator and reference spectrum into account, two categories of calibration procedures can be distinguished: Correction of the spectral mismatch by measuring / knowing the relative spectral responsivity of reference *and* test device as well as measuring / knowing the relative spectral irradiance of the simulator. In order to avoid the measurement of the spectral responsivity of the test PV device (e.g., a large-area module), a set of a few (typical 4) photocurrent measurements under a pulsed solar simulator without and with different simple cut-off filters can be evaluated to correct for spectral
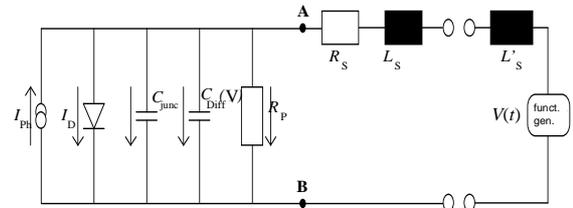

Figure 5: Equivalent circuit diagram for a real solar cell. Between points A and B the voltage $V^*(t)$ is applied.
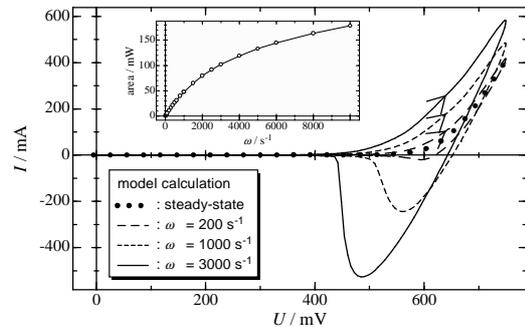

Figure 6: Characteristics simulated with the aid of an improved equivalent circuit diagram, excitation with triangular functions at different frequencies. In the inset, the area between the splitted characteristics as a function of frequency is shown.

mismatch. Such cut-off filters with sufficiently large areas are recommended because of their spectral transmission and blocking behaviour. The use of a flasher is advantageous, because spectral mismatch and thermal load of the filters caused by a flasher are less than that of a steady-state simulator. A long exposure by steady-state radiation sources at about one sun level would destroy the absorbing cut-off filters after a short time.

In the procedure of computational synthesizing the reference solar spectrum, n additional measurements of the short-circuit current (I_1, I_2, ...) under n different spectra ($E_{\lambda,1}(\lambda)$, $E_{\lambda,2}(\lambda)$, ...) of the filtered flasher radiation are needed, where n>=3 is generally adequate. The different spectra are summed up after multiplication with weighting factors (c_1, c_2, ...) such that the sum approximates the AM1.5 reference spectrum (linear optimization):

$$E_{\lambda,\text{AM1.5}}(\lambda) = c_0 E_{\lambda,0}(\lambda) + c_1 E_{\lambda,1}(\lambda) + c_2 E_{\lambda,2}(\lambda) + ...$$

To obtain the short-circuit current under standard test conditions, all the measured short-circuit current components must be added up using the same weighting factors determined by the optimization of the reference spectrum.

$$I_{\text{STC}} = c_0 I_0 + c_1 I_1 + c_2 I_2 + ...$$

The validity of the superposition principle and the linearity of the cells at irradiance levels under the applied irradiance levels (0.2 to 1 sun) during the short-circuit current *measurements* can be taken for granted. It is advantageous in the *computational* superposition of the spectra that it is possible to include spectra in the evaluation with more than 100% or less than zero (see, e.g. Fig. 7).

6. SUMMARY AND CONCLUSION:

While the different transient distortions of all kinds of solar cells and mini-modules under pulsed solar irradiation can be minimized using simple series of measurements and evaluation methods, the application of these correction procedures to large-area PV modules is straightforward, because the electronic equipment and the filters needed can be adapted. Different cell technologies require different specific correction procedures summarized in section 3 to obtain a more accurate calibration of *I-V* characteristics under flasher irradiation. The shifting algorithm is most suitable for all crystalline solar cells due to the voltage-independent photocurrent, i.e. due to the validity of the superposition principle. A-Si and CIS solar cells, however, should be calibrated by the procedure of linear extrapolation, being supplemented, if necessary, by scanning the small voltage range
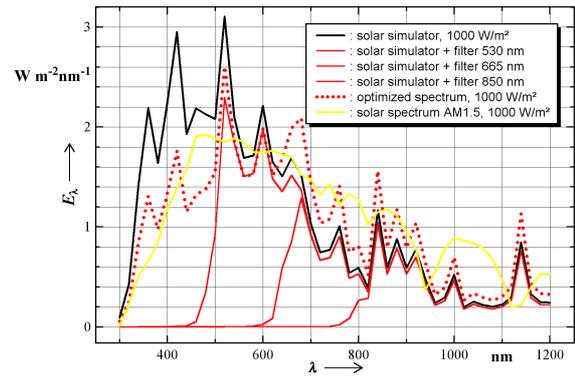

Figure 7: Computational synthesis of the reference solar spectrum by applying a linear optimization:
$$E_{\lambda,\text{opt}} = 0.61 * E_{\lambda,\text{simulator}} + 0.39 * E_{\lambda,\text{OG530}}$$
$$+ 0.51 * E_{\lambda,\text{RG665}} - 0.19 * E_{\lambda,\text{RG850}}$$

between the expected MPP and the open-circuit voltage in order to determine this section without noticeable distortion.

The procedure for the correction of the spectral mismatch presented in section 5 is, in particular, applicable to flasher-based calibrations. The transient errors in the flasher calibrations of a-Si or high-quality c Si solar cells can be reduced from up to >20% to <1% and the errors in spectral mismatch can be reduced from, e.g., 10% to 2%, without knowing the relative spectral responsivity of the test PV device.

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