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Christos Monokroussos
TUV Rheinland

Harald Müllejans
European Commission

Qi Gao
TÜV Rheinland (Shanghai) Co., Ltd.

I-V translation procedure for higher accuracy and compliance with PERC cell technology requirements

Christos Monokroussos[1], Harald Müllejans[2], Qi Gao[1], Werner Herrmann[3]
[1] TÜV Rheinland (Shanghai) Co., Ltd., Shanghai, P.R. China
[2] European Commission*, Joint Research Centre, Ispra, Italy
[3] TÜV Rheinland Energy GmbH, Cologne, Germany
Email: Christos.Monokroussos@tuv.com

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ABSTRACT: The aim of this work was to re-evaluate the correction procedure 2 detailed in the IEC 60891, ed.2, because deviations (within 0.5% in P_{MAX} and 1.0% in V_{OC}) in the region between the maximum power point and open-circuit voltage have been observed between experimental and translated *IV* curves in PERC module types. The equations used in correction procedure 2 were revised to account for: 1. non-linear scaling of V_{OC} against logarithmic irradiance, 2. irradiance-dependent temperature coefficient of voltage, 3. backward compatibility of *IV* translation and 4. temperature dependence of series resistance. The new modified set of equations showed a reduction in the observed deviations between translated and measured *I-V* curves, when compared to the use of the original formulas. The improvements are noticeable in V_{OC}, where accuracy gains up to 2.5% have been observed. Smaller in magnitude (up to 0.3%) but systematic accuracy gains were also observed in P_{MAX}.

Keywords: IEC 60891, correction procedure 2, *I-V* correction, *I-V* translation, temperature, irradiance

1 Introduction

The electrical performance of PV devices is assessed through measurement of current-voltage characteristics (*I-V* curves) and extracting the relevant parameters such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and maximum power (P_{MAX}). IEC standards in general require reporting of the results for defined irradiance and device temperature, whereas the actual conditions during *I-V* measurement inevitably will deviate from these conditions. Therefore, it is necessary to use *I-V* curve translation to correct the measured *I-V* curves from the measurement conditions to the reporting conditions (figure 1).

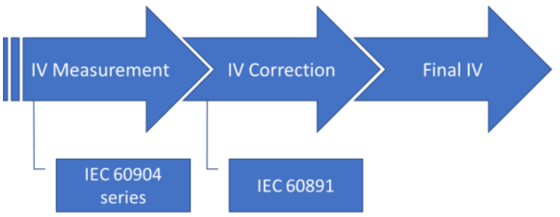

Figure 1: General test procedure for measurement and translation of *I-V* curves with corresponding relevant standards.

IEC 60891 [1] currently describes three different procedures for temperature and irradiance translation. In 1987 the 1st edition of the standard was published that introduced procedure 1. It is based on the simplified single-diode model and relies on the principle of superposition of the currents at all voltages, which assumes that the diode current does not depend on photocurrent. Correction procedures 2 and 3 were introduced in the 2nd edition of the standard published in 2009. Similar to correction procedure 1, correction procedure 2 is based on the simplified single-diode model. The semi-empirical translation equations contain five *I-V* curve correction parameters which can be determined by measurement of *I-V* curves at different temperature and irradiance conditions. An advantage of correction procedure 2 is that it always produces complete *I-V* curves when translating to higher irradiance, which is achieved as the measured V_{OC} is again translated to V_{OC} of the translated curve. This is not the case for correction procedure 1, when translating to a higher irradiance level, where the translated curve can reach up to V_{OC} only if the *I-V* curve has been measured sufficiently beyond the usual measurement range.

Correction procedure 3 is based on the linear interpolation or extrapolation of multiple measured *I-V* characteristics and requires no correction or fitting parameters [2]. It is noted that in the current draft of IEC 60891, which is currently being revised, correction procedure 4 has been proposed [3], which is most suitable when the correction parameters are unknown and cannot be determined. The procedure is fundamentally based on the single-diode model and requires only the bandgap of the material and the number of cells connected in series to be known.

The aim of this work was to re-evaluate correction procedure 2, because deviations (in most cases within 0.5% in P_{MAX} and 1% in V_{OC} in the irradiance range of 600-1 200Wm^{-2}) in the region between the maximum power point and open-circuit voltage have been observed between experimental and translated *I-V* curves in PERC module types. The following paragraphs discuss the motivation for the proposed changes in correction procedure 2. In the end a validation of the new correction procedure 2 against experimental data measured at various temperatures and irradiances is performed for different c-Si PERC and thin-film technologies.

2 Limitations of the original method and review of proposed changes

2.1 Non-linear scaling of V_{OC} against irradiance

In IEC 60891, ed. 2 voltage scales proportionally to the logarithm of irradiance. This assumption enables voltage translation to different levels of irradiance based on a linear relationship between $V_{OC,STC}/V_{OC}(G)$ and $\ln(1\,000/G)$. Strictly speaking though the scaling of voltage with the logarithm of irradiance is non-linear and may introduce deviations in the translated *I-V* curves in the proximity of V_{OC}. The magnitude of these deviations is smaller for conventional solar cell technologies such as back surface field (BSF) c-Si technologies, than newer technologies such as passivated emitter rear contact (PERC) c-Si. It is also noted that the effect can be reproduced by synthetic data deriving from the single-diode model, but its magnitude is also smaller.

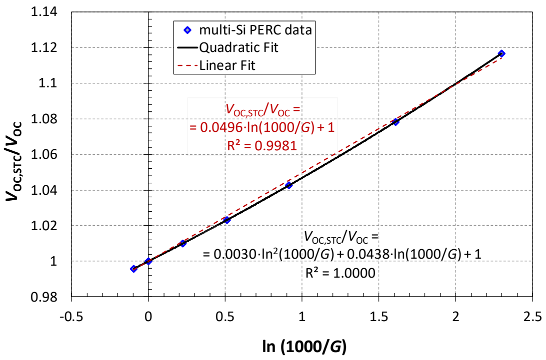

Figure 2: The graphs shows the necessity for two V_{OC} irradiance correction factors B_1 and B_2 to account for non-linear scaling of $V_{OC,STC}/V_{OC}(G)$ with ln(1 000/G).

When fitting experimental data, it was observed that a quadratic logarithmic model can provide improved accuracy in the irradiance scaling of voltage translation for both measurements and simulations. Figure 2 shows a comparison between the linear logarithmic and the quadratic logarithmic approximation against measurements of V_{OC} at various levels of irradiance for a commercial multi-PERC c-Si PV-module. It is also shown that a quadratic formula can provide improved accuracy in the voltage translation of irradiance scaling. Based on these observations an empirical irradiance function, $f(G)$ is introduced as follows:

$$f(G)=\frac{V_{OC,STC}}{V_{OC}(G)} = B_2\cdot\ln^2\left(\frac{1\,000\mathrm{Wm}^{-2}}{G}\right)+B_1\cdot\ln\left(\frac{1\,000\mathrm{Wm}^{-2}}{G}\right)+1 \quad (1)$$

where B_1 and B_2 are fitting constants for open-circuit voltage, which are linked with the diode thermal voltage V_t of the p-n junction and the number of cells n_S serially connected in the DUT. When B_2 equals to zero the formula reduces to the same linear model, which was used in correction procedure 2 of IEC 60891, ed. 2. Lastly, it is important to note that the quadratic model not only allows for *more accurate I-V translation*, but also its parameters can be determined *without additional measurement effort* comparing to the procedures employed in IEC 60891, ed. 2.

2.2 Irradiance-dependent temperature coefficient of voltage

Correction procedure 2, and in general all correction procedures detailed in IEC 60891, ed. 2 assume that the temperature coefficient of voltage does not depend on irradiance. It is generally recommended though that the measured level of irradiance shall be within ±30% of the level of irradiance at which temperature coefficients were determined to ensure the accuracy of *I-V* translation.

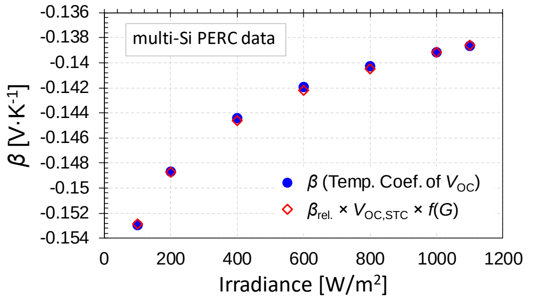

Figure 3: Comparison between the experimentally measured temperature coefficent of voltage, β, at various levels of irradiance and the product of irradiance function $f(G)$ and β determined at STC for a multi-Si PERC module type.

It has been previously reported that the temperature coefficient for voltage varies with the level of irradiance for both c-Si and thin-film technologies [4, 5]. Generally, these reports agree that the temperature coefficient of voltage decreases at lower irradiance, but also show that some technologies are more susceptible to this effect. Such effects can be readily reproduced in c-Si PERC technologies, which are commonly available in the market.

This work shows for the first time that the irradiance-dependent temperature coefficient of voltage scales proportionally with the empirical irradiance function, $f(G)$, which was introduced in section 2.1. Figure 3 shows that the comparison between the experimentally determined temperature coefficient of voltage β, at various irradiance levels and the product of irradiance function $f(G)$ with β determined at STC for a c-Si PERC module type. It is shown that *the product of f(G) with β provides an accurate approximation of the irradiance dependence of the temperature coefficient of voltage*. Similar agreement was also observed for other two types of c-Si PERC modules and also synthetic data derived from the single-diode model. The complete results of the verification analysis will be presented elsewhere.

2.3 Backward compatibility of *IV* translation

Correction procedure 2 allowed for a direct translation (#1→#2) from a measured condition #1 of irradiance, G_1 and temperature, T_1 to a translated condition #2 of irradiance G_2, and temperature T_2. However, doing so introduced inaccuracies, as typically the correction parameters have not been necessarily determined in condition #1 (in most cases they are determined at STC). Such inaccuracies also compromised the forward-backward compatibility of the method; in other words re-translating the translated curve at condition #2 back to the original condition #1 resulted in an *I-V* curve different from the original. The observed deviations, although small in magnitude (approx. 0.5%), raised concerns on the physical correctness of the method on a theoretical level.

The proposed solution involves intermediate translation to the condition at which the correction parameters have been determined (#1→STC→#2). Since correction parameters are routinely determined at STC, STC is used as intermediate correction condition. The proposed changes have introduced modifications in the formulas of correction procedure 2, which are explained below.

A) Current translation at different temperature and irradiance

Correction procedure 2 in IEC 60891, ed. 2 handled the current translation as in formula (2):

$$I_2 = \frac{G_2}{G_1} \cdot I_1 \cdot \left(1 + \alpha_{\mathrm{rel}} \cdot (T_2 - T_1)\right) \tag{2}$$

which is an approximation that holds true when T_1 and T_2 do not considerably differ to 25°C. The exact and more physically transparent formula however is given in formula (3), where an intermediate correction to STC is introduced between conditions #1 and #2:

$$I_2 = \frac{G_2}{G_1} \cdot I_1 \cdot \frac{\left(1 + \alpha_{\mathrm{rel}} \cdot (T_2 - 25°\mathrm{C})\right)}{\left(1 + \alpha_{\mathrm{rel}} \cdot (T_1 - 25°\mathrm{C})\right)} \tag{3}$$

B) Voltage translation at different temperature and irradiance

The second edition of IEC 60891, handled voltage translation at different temperature and irradiance independently, so there is no inter-dependence in the translation. Voltage is assumed to shift proportionally by the product of the measured voltage $V_{OC,1}$, the relative temperature coefficient of voltage, β_{rel} and the difference between the target and measured temperature $\Delta T = T_2 - T_1$. Irradiance scales proportionally with the product of B_1 and $\ln(G)$, as discussed in 2.1.

At V_{OC}, series resistance related factors are eliminated from the formulas and one arrives to the simplified general expression:

$$V_{\mathrm{OC2}} = V_{\mathrm{OC1}} + V_{\mathrm{OC1}} \cdot \left[\beta_{rel} \cdot (T_2 - T_1) + B_1 \cdot \ln\left(\frac{G_2}{G_1}\right) \right] \tag{4}$$

A number of changes are introduced in formula (4). Firstly, for the temperature translation of voltage correction, $V_{OC,1}$ is replaced by $V_{OC,STC}$ (at 1 000 W m^{-2} and 25 °C) in formula (3), because β_{rel} has been normalized to $V_{OC,STC}$ by its definition. Furthermore, β_{rel} is multiplied with the empirical irradiance correction factor $f(G)$, as in (1), to account for changes of β_{rel} with irradiance, which was discussed in section 2.2. This is a significant change, as now irradiance and temperature corrections are no longer independent of one another. For the irradiance scaling of voltage correction, a quadratic formula is introduced as in section 2.1. Lastly, an intermediate translation procedure to STC is introduced (#1→STC→#2). With these considerations in mind, formula (4) is revised as follows:

$$V_{\mathrm{OC2}} = V_{\mathrm{OC1}} + V_{\mathrm{OC,STC}} \cdot \left\{ \begin{array}{l} \beta_{\mathrm{rel}} \cdot \left[\begin{array}{l} f(G_2) \cdot (T_2 - 25°\mathrm{C}) - \\ f(G_1) \cdot (T_1 - 25°\mathrm{C}) \end{array} \right] \\ + \dfrac{1}{f(G_2)} - \dfrac{1}{f(G_1)} \end{array} \right\} \tag{5}$$

It is noted that similarly with the practice followed in formula (4), the analysis was carried out at V_{OC}. Hence, series resistance related terms are eliminated in formula (5).

The described changes *improved the accuracy of translation, which becomes apparent in the region between P_{MAX} and V_{OC}.* An example of the improvement is illustrated in figure 4, where measurements at different levels of temperature at 1 000W·m^{-2} were translated to STC for a commercial c-Si PERC module type. The graph compares the results of correction procedure 2 in its original form (as in IEC 60891, ed. 2) and its revision proposed here. Signficant gains in accuracy have been achieved particularly for P_{MAX} (~0.2%) and V_{OC} (~1%) and in the region in between.

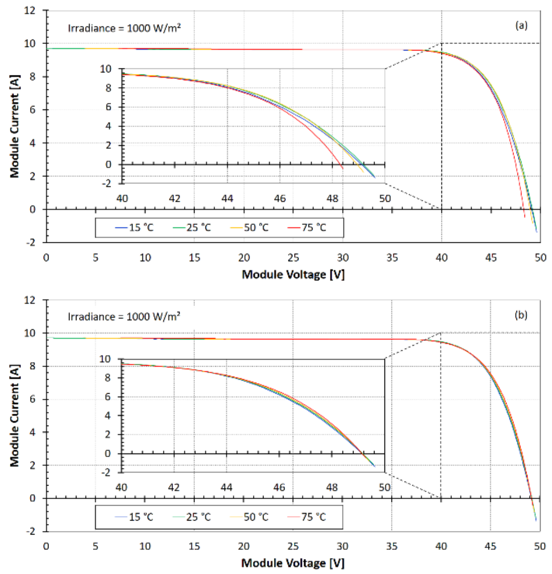

Figure 4: Temperature translation of measured *I-V* curves of a c-Si PERC module type at different temperatures to STC according to IEC 60891, ed. 2 correction procedure 2 (a) and its revision (b). The reference *I-V* curve at STC is shown in green in both graphs. Gains in accuracy have been achieved particularly in the region between P_{MAX} and V_{OC}.

2.4 Temperature dependence of series resistance

Correction procedure 2 as proposed in IEC 60891, ed. 2 assumes a fixed series resistance, R'_S, which is determined by performing measurements at various levels of irradiance and its temperature coefficient, κ, which is determined by fitting measurements at various temperature levels. The method accounts for the temperature dependence of series resistance from condition #1 at temperature, T_1, to condition #2 at temperature T_2. Hence, the voltage shift introduced by the series resistance between #1 and #2 is:

$$\Delta V = V_2 - V_1 = R'_S \cdot (I_2 - I_1) \text{-} \kappa' \cdot I_2 \cdot (T_2 \text{-} T_1) \tag{6}$$

Formula (6) holds true, as long as R'_S has been determined at temperature T_1. In most of the cases R'_S is determined at 25°C. Hence, an error is introduced, when

T_1 differs to 25°C, because formula ([6](#)) accounts only for the temperature dependence of R'_S from T_1 to T_2, but not for its dependence from 25°C to T_1, which will affect the value of base R'_S. The proposed change modifies the base value of R'_S at temperature T_1 by introducing the term R'_{S1}, which is the value of series resistance at temperature T_1. Hence, formula (6) can be rewritten as:

$$\Delta V = V_2 - V_1 = R'_{S1} \cdot (I_2 - I_1) - \kappa' \cdot I_2 \cdot (T_2 - T_1) \qquad (7)$$

$$\text{where} \quad R'_{S1} = R'_S + \kappa' \cdot (T_1 - 25°\text{C}) \qquad (8)$$

When not accounting for R'_{S1} errors in P_{MAX} are relatively small (<0.2%) when T_1 is measured within 25±10°C. In an extreme scenario where long range irradiance ($\Delta G \geq 1\,000$ Wm^{-2}) and temperature corrections ($\Delta T \geq 50$°C) are practiced the effect can contribute errors up to 1.0% in P_{MAX}, as shown in [figure 5](#). We note that although the shown scenario is useful in illustrating the effects, in reality it is rather unlikely that a low-irradiance and low-temperature measurement will be translated to high-irradiance and high-temperature. Generally, *addressing the temperature dependence of series resistance results in accuracy improvements in P_{MAX} of the order of 0.1-0.2%.*

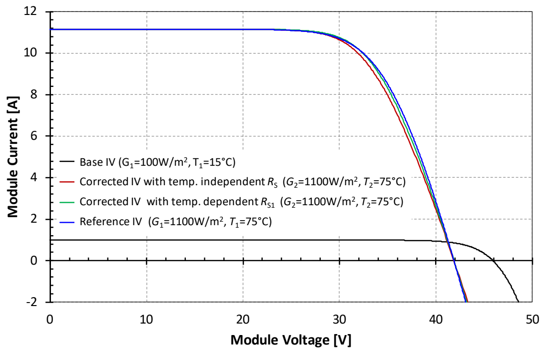

Figure 5: Comparison of translated *I-V* curves which do not account (red curve) and do account (green curve) for R'_{S1} in the translation procedure, when long temperature ($\Delta T = 60$°C) and irradiance ($\Delta G = 1\,000$ Wm^{-2}) corrections are performed. The initial *I-V* curve (black) and a reference curve (blue) measured at the target irradiance and temperature is also given for comparison.

3 Revised Formulas for Correction Procedure 2

Considering the modifications proposed in section [2](#), the equations of correction procedure 2 for current and voltage translation were revised. The proposed equations are summarized as follows:

$I_2 = \frac{G_2}{G_1} \cdot I_1 \cdot \frac{(1 + \alpha_{rel} \cdot (T_2 - 25°\text{C}))}{(1 + \alpha_{rel} \cdot (T_1 - 25°\text{C}))}$	(3)
$V_2 = V_1 + V_{OC,STC} \cdot \left\{ \begin{array}{l} \beta_{rel} \cdot \left[\begin{array}{l} f(G_2) \cdot (T_2 - 25°\text{C}) - \\ f(G_1) \cdot (T_1 - 25°\text{C}) \end{array} \right] \\ + \frac{1}{f(G_2)} - \frac{1}{f(G_1)} \end{array} \right\}$ $- R'_{S1} \cdot (I_2 - I_1) - \kappa' \cdot I_2 \cdot (T_2 - T_1)$	(7)
where $f(G) = \frac{V_{OC,STC}}{V_{OC}(G)}$ $= B_2 \cdot \ln^2\left(\frac{1\,000 Wm^{-2}}{G}\right) + B_1 \cdot \ln\left(\frac{1\,000 Wm^{-2}}{G}\right) + 1$	(1)
$R'_{S1} = R'_S + \kappa' \cdot (T_1 - 25°\text{C})$	(8)
and $V_{OC,STC} = \frac{V_{OC1} \cdot f(G_1)}{1 + \beta_{rel} \cdot (T_1 - 25°\text{C}) \cdot f^2(G_1)}$	(9)

It is noted that formula ([9](#)) is derived from equations ([1](#)) and ([7](#)) and can be used if the V_{OC} of the DUT at STC is unknown. If V_{OC} at STC is known, formula ([9](#)) does not need to be used, and its value can be replaced by the measurement. B_1 and B_2 are irradiance fitting constants and can be determined following the procedure described in section [2.1](#), the series resistance, R'_S and its temperature coefficient, κ' can be determined following the procedures described in IEC 60891, ed. 2 without modifications.

Another consequence of the proposed changes is the impact to equivalent cell temperature (ECT), which is the topic of international standard IEC 60904-5 [[6](#)]. ECT is fundamentally based on correction procedure 2, hence, its formula should also be modified to the following expression to be aligned with the proposed changes:

$$ECT = 25°\text{C} + \frac{1}{\beta_{rel} \cdot f^2(G)} \cdot \left(\frac{V_{OC}}{V_{OC,STC}} \cdot f(G) - 1 \right) \qquad (10)$$

4 Verification of Revised Correction Procedure 2

A validation of the new correction procedure 2 has been performed utilising experimental data of 3 different c-Si PERC modules, 1 thin-film CdTe module and also synthetic data derived from the single-diode model. The employed methodology is based on the comparison of measurements, or simulations at different levels of irradiance and temperature with the reference curve at STC. IEC 61853-1 [[7](#)] was used as a base for the selection of irradiance and temperature conditions resulting in 22 different *I-V* curves that correspond to irradiance levels ranging between (100 - 1 100) Wm^{-2} and temperatures between (15 – 75)°C. Out of these 22 *I-V* curves, 21 are different to STC. These 21 *I-V* curves were translated to STC and a comparison is made in terms of I_{SC}, V_{OC} and P_{MAX} with the reference curve measured at STC for both the proposed revised (this work) and original correction procedure 2 as in IEC 60891, ed. 2. As metrics for the comparison and validation, the mean bias error (MBE), the root mean square error (RMSE) over the whole IEC 61853-1 matrix and also point-to-point deviation graphics are employed.

In this paper only results for PERC module type #3 are shown, while the complete data will be presented elsewhere. Figures [6](#) and [7](#) show the deviations after correction to STC over the whole IEC 61853-1 matrix for irradiance and temperature for I_{SC}, V_{OC} and P_{MAX} for the correction procedure 2, as in IEC 60891, ed. 2 and its proposed revision. [Table I](#) displays a comparison of

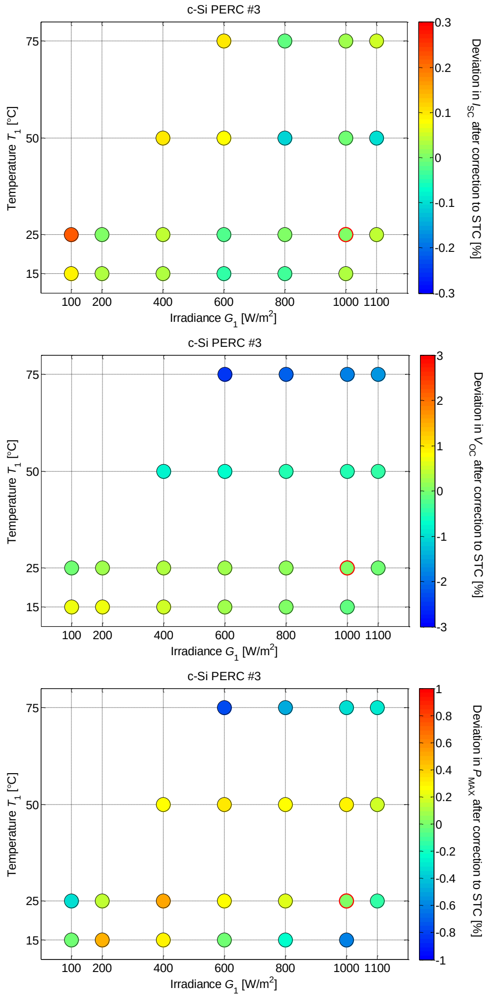

Figure 6: Deviation of translated *I-V* curves to STC utilising the *correction procedure 2 as in IEC 60891, ed. 2* for a c-Si PERC module type over the whole IEC 61853-1 irradiance-temperature matrix for I_{SC}, V_{OC} and P_{MAX}. It is shown that worst cases errors for I_{SC}, V_{OC} and P_{MAX} are 0.22%, 2.51% and 0.78% respectively of the measured values.

methods in terms of MBE, RMSE and worst case agreement over the whole IEC 61853-1 irradiance-temperature matrix. *The application of the new modified equations showed a clear reduction in deviation between translated and measured I-V curves, when compared to the use of the original equations.* The improvement is particularly noticeable in V_{OC}, where accuracy gains up to 2.5% have been observed. Furthermore, smaller in magnitude (up to 0.3%) but systematic accuracy gains are observed in P_{MAX}. The proposed modification achieved MBE and RMSE, which is smaller than 0.1% for I_{SC} and V_{OC}. For P_{MAX} MBE is also within 0.1%, while RMSE is within 0.3%. It is noted that measurement uncertainty of the irradiance-temperature matrix and accuracy of the translation would both affect the level of agreement. Since the uncertainty in the irradiance-temperature matrix measuremens varied within 1.5-2.0% (k=2) in P_{MAX} and within 0.6-0.8% (k=2) in V_{OC}, the numbers reported here should be understood as conservative estimates of the accuracy of the method.

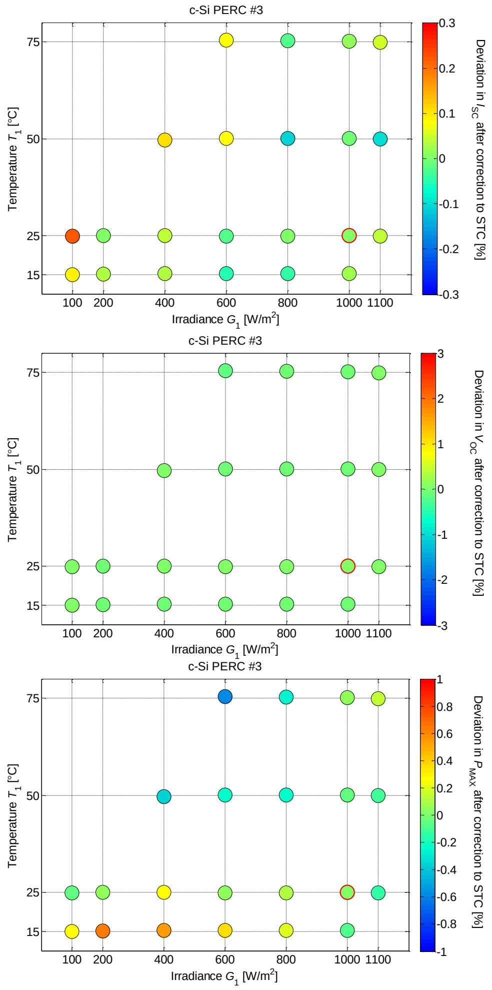

Figure 7: Deviation of translated *I-V* curves to STC utilising the *revised correction procedure 2* for a c-Si PERC module type over the whole IEC 61853-1 irradiance-temperature matrix for I_{SC}, V_{OC} and P_{MAX}. It is shown that worst case errors for I_{SC}, V_{OC} and P_{MAX} are 0.22%, 0.15% and 0.58% respectively of the measured values. It is noted that measurement uncertainty and accuracy of the translation would both affect the level of agreement.

Table I: Comparison of correction methods in terms of MBE, RMSE and worst case agreement over the whole range of IEC 61853-1 irradiance-temperature matrix.

Correction procedure 2 (IEC 60891, ed. 2)

	MBE	RMSE	Worst Case
I_{SC}	0.024%	0.073%	0.220%
V_{OC}	0.366%	0.944%	2.510%
P_{MAX}	0.002%	0.347%	0.780%

Correction procedure 2 (proposed revision)

	MBE	RMSE	Worst Case
I_{SC}	0.022%	0.073%	0.220%
V_{OC}	0.021%	0.053%	0.150%
P_{MAX}	0.026%	0.284%	0.580%

5 Conclusion

The aim of this work was to re-evaluate the correction procedure 2 introduced into IEC 60891 in ed.2 published in 2009, because some deviations between experimental and translated *I-V* curves had been observed. The equations used in correction procedure 2 have been re-examined, which resulted in the introduction of a number of improvements in the original set of equations regarding: 1. non-linear scaling of V_{OC} against logarithmic irradiance, 2. irradiance-dependent temperature coefficient of voltage, 3. backward compatibility of *IV* translation and 4. temperature dependence of series resistance. Furthermore, the application of the new modified set of equations showed a clear reduction in the observed deviations between translated and measured *I-V* curves, when compared to the use of the original formulas. The improvements are particularly noticeable in V_{OC}, where accuracy gains up to 2.5% have been observed. Smaller in magnitude (up to 0.3%) but systematic accuracy gains were also observed in P_{MAX}. Additional verification was performed against thin-film modules and synthetic data, and will be presented elsewhere. In view of these results, *it is recommended to revise the formulas for correction procedure 2 in the IEC 60891 in the ongoing revision*.

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