Current-Voltage Translation Procedure for PV Generators in the German 1,000 Roofs-Programme

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1. Introduction

The price of PV modules an thus the price of PV generators is mostly determined by their electrical output as specified by the manufacturer. In general these specified data can only be checked by control measurements that have to be carried out on site. Such performance measurement consists of tracing the IV-characteristic and determination of the maximum power point (MPP) on the IV-curve. Because the output of PV arrays depends strongly on the operation conditions such as solar irradiance G, module temperature T and spectral irradiance distribution $E(\lambda)$ in a second step the measured array characteristic has to be transposed to the commonly used "Standard Test Conditions (STC)", which are defined as: G_{STC} = 1000 W/m², T_{STC} = 25°C, $E_{STC}(\lambda)$ = AM 1.5 according to IEC 904-3.

The translation of array measurements to STC is done by application of so-called mathematical procedures for temperature and irradiance correction. Fig. 1 illustrates these two steps of characterizing of the array output based on outdoor measurements.

Both steps are affected with uncertainties which are the measuring uncertainty U_{meas} and accuracy of translation U_{corr} from which the resultant overall uncertainty U_{tot} is derived by applying the usual method for the combination of variances.

$$U_{tot} = \sqrt{U^2_{meas} + U^2_{corr}}$$

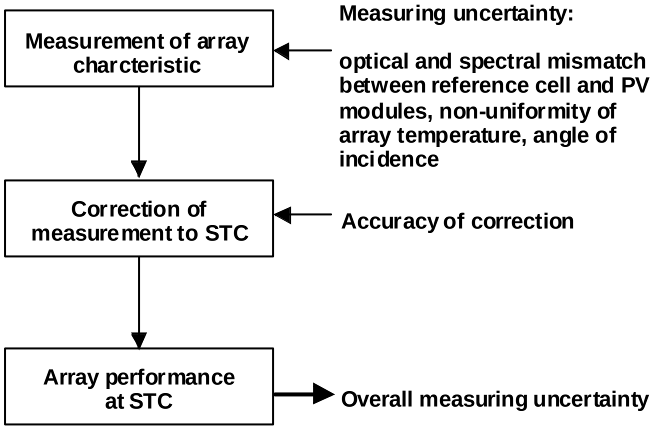

Fig. 1: Steps for characterisation of the PV array performance

Control measurements on PV generators should aim at keeping both uncertainties as low as possible. This is because the overall measuring uncertainty U_{tot} has to be added to the tolerance of fabrication U_{fab} given by the manufacturer when specifying the level of acceptable reduced array output. This level of acceptance LOA is given by the expression

$$LOA = U_{fab} + U_{tot}$$

This means that measured reduced outputs of PV arrays below this level have to be accepted. The influence of U_{corr} on LOA is illustrated in fig.2 which is based on the assumption that U_{fab} is given with 5% and U_{meas} lies in the range of 5-10%.

From fig. 2 can be concluded that a variation in U_{corr} from 0% to 5% leads to a variation of the acceptance level by maximum 2%.

The measurement uncertainty U_{meas} was in many cases the object of examinations in the past, but no findings exist to date regarding the uncertainty due to temperature and irradiance correction of IV-measurements to STC. The objective of the presented work is to find out which translation accuracy are reached in practise and to deduce measures for PV array performance measurements how to minimize it.

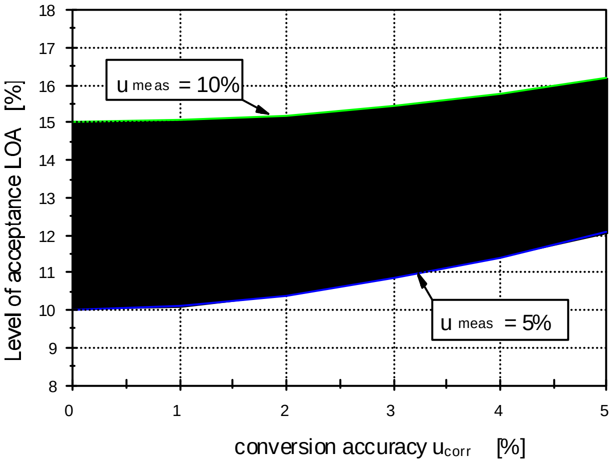

Fig. 2 Level of acceptance for reduced output of PV arrays

2. Translation procedures in use

For the purpose of temperature and irradiance correction of measured IV-curves to STC various mathematical algorithms (correction procedures) have been presented in the past which can be divided into algebraic and numerical procedures [1,2,3,4,5,6].

2.1 Algebraic translation procedures

Algebraic translation procedures are based on the specific performance data of PV modules which are mostly the temperature coefficients and the series resistance. They use two separate conversion equations for current and voltage which are applied to any point of the IV-characteristic and which have the following structure

$$I_2 = I_1 + \Delta I = I_1 + f\,(I_1, G_1, T_1, \alpha, ...) \text{ or}$$
$$I_2 = I_1 \cdot FI = I_1 \cdot f\,(I_1, G_1, T_1, \alpha, ...)$$

$$V_2 = V_1 + \Delta V = V_1 + f\,(V_1, I_2, G_2, T_2, \beta, R_s, ...)$$

where

α = temperature coefficient of short-circuit current
β = temperature coefficient of open-circuit voltage
R_s = series resistance
T = module/array temperature
G = solar irradiance

Index "1" is related to the measurement and Index "2" to the transposed conditions which usually are STC. As a result of temperature and irradiance correction the IV-curve at STC consists of the same number of points as the measured curve.

For the first time in 1987 an algebraic correction procedure for PV modules was passed as IEC standard [1]. Herein the conversion equations for voltage and current (sandstrom equations) contain beside the temperature coefficients (α, β) and the series resistance R_S a so-called curve factor K, by which the correction behaviour in the MPP range is described. Because in case of the parameters R_S and K the conditions on PV module level cannot be transferred to PV arrays which represent a series and parallel connection of PV modules the IEC procedure is not qualified for temperature and irradiance correction on PV generators.

Algebraic correction procedures can easily be applied to measurements, because the used functional equations are of explicit structure. Beside this the following disadvantages have to be mentioned:

a) The application assumes that the module specific parameters are known. In the case of the temperature coefficients α and β they can be taken from the module data sheets but in most cases other parameters are not existent. Especially the influence of R_s on the declining part of the IV-curve is of importance for the accuracy of the translation.

b) Because of the structure of the correction equations that effect voltage and current offsets at the limits of measuring range the short-circuit current I_{sc} and the open-circuit voltage V_{oc} of the transposed IV-curve have to be extrapolated. To limit uncertainties due to this fact the solar irradiance for acceptable measurements has to take values above 600 W/m².

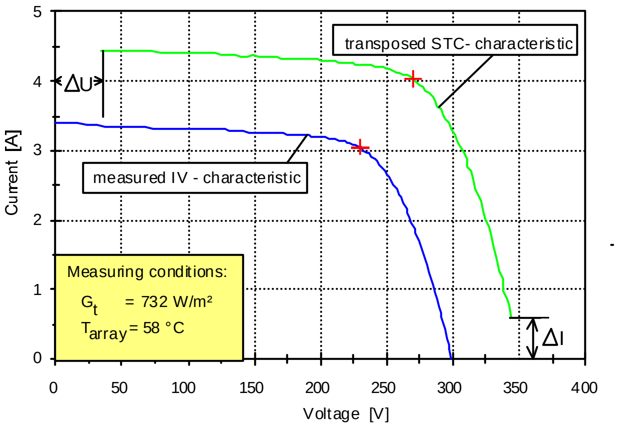

Fig. 3: IV-curve transposition with algebraic correction procedures

2.2 Numerical translation procedures

Another approach of converting measured IV-curves to Standard Test Condition is to use an analytic description of solar cells which is based on semiconductor physical phenomena. Herein solar cells are modelled by an equivalent circuit diagram consisting of several discrete components (variable double exponential model). The relationship between current and voltage is expressed by a two-exponential equation containing seven modelling parameters

$$I = I_{PH} - I_{S1}\left\{\exp\left(\frac{V+I\cdot R_S}{A_1\cdot V_T}\right)-1\right\} - I_{S2}\cdot\left\{\exp\left(\frac{V+I\cdot R_S}{A_2\cdot V_T}\right)-1\right\} - \frac{V+I\cdot R_S}{R_P}$$

where

I_{ph} : generated photocurrent = f (G, T)
I_{s1}, I_{s2} : dark saturation currents = f (T)
A_1, A_2 : diode ideality factors
R_s : series resistance
R_p : shunt resistance

V_T is equal to kT/e with k as Bolzman constant and e as elementary charge.

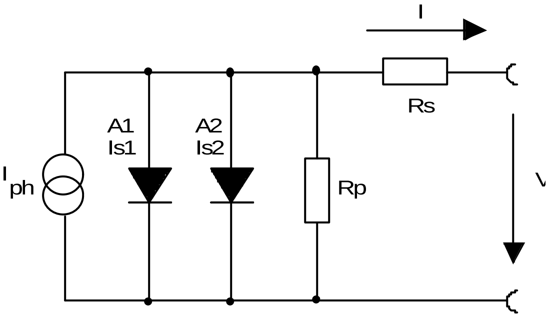

Fig. 4: Electrical equivalent circuit for crystalline silicon solar cells

This implicit equation can only be solved using numerical (iterative) techniques. Starting with initial parameter values the best parameter set is determined by minimisation of a proper object function, that expresses the difference between the experimental and the theoretical IV-characteristics (modified least mean square fit).

For practise the advantage of numerical correction procedures is that no module specific parameters need to be known. On the other hand there is no standardised computer software which means that only skilled personnel can do the calculations. Additionally it is observed that different IV-measurements of the same PV array lead to different parameter sets. The parameter sets are not in relation to the measurable module or array specific parameters.

3. Round-robin test on translation procedures

To date the standardisation of correction procedures for PV array measurements on IEC level are under discussion and no harmonised results are to be expected for the next years. Because of this, at PV measuring laboratories and institutes many different procedures are in use and consequently the conversion results are subject to a certain scattering when the same IV-measurement data set is taken as input.

Especially for the German 1000 Roofs Programme where several institutes are combined within the "Intensive Measurement and Evaluation Programme" the need became apparent to have a uniform translation procedure to ensure a comparability of the results.

Table 1 shows the result of an enquiry regarding which correction procedures are in use at the different member institutes. Of the 9 groups invited for the round-robin test, 4 groups use numerical computer-based models, while the other 5 use algebraic translation expressions. It was obvious that all procedures differ from each other: whether the mathematical expres-sions for current or voltage or the data base for PV module coefficients in the case of algebraic pro-cedures or the fitting method in the case of numerical procedures.

No.	**Participant**	Place	**Correction procedure**
1	Research Centre Rossendorf	Rossendorf	algebraical
2	FhG-ISE	Freiburg	algebraical
3	ISFH	Hameln	numerical
4	Joint Research Centre	Ispra (Italy)	algebraical
5	University of Oldenburg	Oldenburg	numerical
6	University of Siegen	Siegen	numerical
7	TÜV Rheinland	Cologne	algebraical
8	WIP	Munich	algebraical
9	ZSW	Stuttgart	numerical

Table 1: Participants of the round robin test

No.	**Type of module**	**Ns**	**Np**	**Gt W/m²**	**Tm °C**
1	AEG, PQ 10/40 H44D	13	6	904	57
2	AEG, PQ 10/40 H44D	13	6	638	46
3	Siemens, SM50-18A2	14	17	880	56
4	Siemens, SM50-18A2	14	17	698	56
5	Kyocera, LA361 J48	24	12	993	52
6	Kyocera, LA361 J48	24	12	558	35
7	BP Solar, BP 275	16	1	732	58
8	BP Solar, BP 252	6	1	981	63
9	ASE, MQ 40/52	4	1	788	23
10	ASE, PQ 40/50	6	1	798	52
11	Siemens, M55	6	1	711	62
12	ASE, PQ 72 D-L	9	1	849	47

Table 2: Data base for the round robin test

This occasion was used to carry out a round robin test to find out which translation accuracies are achieved in practice. The common data base were 12 measured array characteristics. On the whole the data set comprises 9 different types of PV modules at which in 3 cases two measurements at different solar irradiance and array temperature were be presented. Table 2 summarises the basic information of raw data sets for the round robin tests, where Ns represents the number of modules connected in series and Np the number of strings in parallel.

On the assumption that every correction procedure has the same weight the STC results of all participants were taken to calculate the mean values of short-circuit current I_{sc}, open-circuit voltage V_{oc}, voltage V_{mpp} and current I_{mpp} at maximum power point seperately for each IV-measurement. In a second step the results of each participant were normalised to these mean values and plotted into two diagrams, from which statements in view of scattering could be drawn.

Fig. 3 illustrates that the predicted I_{SC} and V_{OC} scattered by approximately ± 2% around the group average. Relevant for the accuracy or translation related to the electrical output is the scattering of current and voltage at MPP.

Fig. 4 shows that this scattering lies in the range ±3% which means a resulting scattering of electrical output at STC of 4% at its maximum.

In both diagrams the triangles represent the results related to numerical and the crosses the results related to algebraical correction procedures.

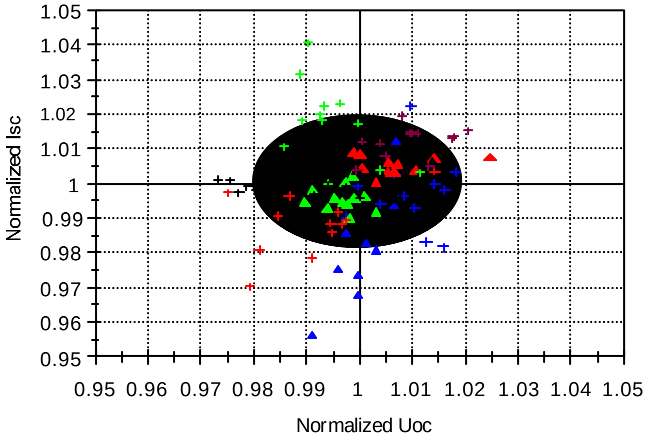

Fig. 3: Scattering of Isc and Voc at STC

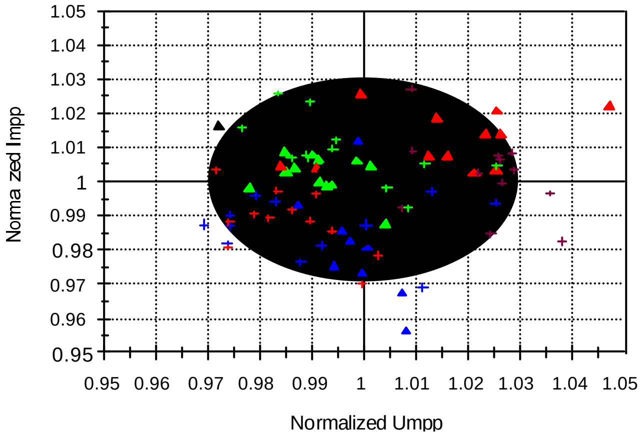

Fig. 4: Scattering of maximum power points at STC

From this results can be concluded that the uncertainty due to translation of measured array characteristics is 4% at its maximum even if only one IV-measurement is existent. According to fig. 1 this leads to an increase of 0.8% to 1.4% to the total measuring uncertainty for PV array performance measurements.

Because the scattering of numerical and algebraical results is nearly the same as a second result it can be stated that there was no difference between algebraic and numerical correction procedures with regard to the accuracy of translation.

4. Uniform translation procedure

From the results of the round-robin test the following requirements for a uniform correction procedure for the German 1000-roofs-programme were concluded:

a) The procedure must be easily applicable, which favours the algebraic procedures

b) The procedure should supply good translation results even when no module specific parameters are known

c) The module and generator specific parameters which are used as inputs to the correction should be deducible from the measurements, so that results are independent of module data given by the manufacturer

An evaluation of the 9 translation procedures of the round-robin test regarding these criteria led to a favouring of the algebraic procedure that was developed at the Joint Research Centre of the European Commission in Ispra [7]. The mathematical expressions for correction of current and voltage are

$$I_{SC,2} = I_{SC,1} \cdot \left\{1 + \alpha \cdot (T_2 - T_1)\right\} \cdot \frac{G_2}{G_1}$$

$$V_{OC,2} = V_{OC,1} \cdot \left\{1 + a \cdot \ln\frac{G_2}{G_1} + b \cdot (T_2 - T_1)\right\}$$

translation equations:

$$I_2 = I_1 \cdot \left(\frac{I_{SC,2}}{I_{SC,1}}\right)$$

$$V_2 = V_1 + \left(V_{OC,2} - V_{OC,1}\right) + R_S \cdot (I_1 - I_2)$$

Name	Module parameter	Default value
α	dimensionless temperature coefficient of I_{SC}	0
b	dimensionless temperature coefficient of V_{OC}	0.06
a	diemensionless irradiance correction factor	-0.004
R_S	series resistance	0 Ω

Table 3: Input data of the algebraic correction procedure developed at the JRC-CEC in Ispra

In its minimal version when only one array measurement exists and no module specific parameters are known a translation accuracy of 4% is achieved by using the default values of table 3, that are valid for crystalline silicon.

The translation accuracy can be improved below 3% when several array measurements at different array temperature and solar irradiance are performed, from which the parameters a, b, α can be determined using linear regression techniques and R_S by optimising the covering of the STC-characteristics in their descending part.

References:

[1] IEC Standard 891 (1987)
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