Significant Improvement in PV Module Performance Prediction Accuracy Using a New Model Based on IEC-61853 Data

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***Abstract*—This paper presents a significant improvement in accuracy for photovoltaic (PV) module performance prediction using a new approach based on IEC-61853 test data. The method is based on the concept of a single diode model and calibrates its performance across a broad set of operating conditions. The new method reduces irradiance-weighted error in maximum power point (MPP) power relative to the standard 6-parameter single diode model, on average across 20 different module types, by 88 % across the entire range of measured irradiance and temperature conditions, while retaining a continuous mathematical representation of the full current-voltage characteristic that allows for accurate off-MPP module modeling.**

I. INTRODUCTION

Accurate calculation of PV module power output at any operating condition is an integral part of correctly predicting overall system performance, and as a result, many different models exist to predict the conversion from irradiance to DC output. These module models can be loosely divided into three main categories: (1) equivalent circuit models that represent the PV module as a simplified circuit, (2) point models that describe the five principal points on an I-V curve, and (3) data-driven models that prescribe how to use reference measured data to predict performance at any condition. The most common method in use today is the single diode equivalent circuit model developed by Desoto and collegues [1], or variants thereof [2], [3]. The single diode model, characterized by Eqn. 1 is easy to use since its parameters can be readily calculated from standard test condition (STC) data included on module datasheets. A set of equations translate the 5 or 6 parameters from their STC values to the particular temperature and irradiance conditions of interest in order to solve for the module current and voltage. However, the single diode model predictions frequently do not match measured values at low irradiance, because the measurements are taken at the high irradiance specified at STC.

$$I = I_L - I_o\left(\exp\left[\frac{V+IR_s}{a}\right]-1\right)-\frac{V+IR_s}{R_{sh}} \qquad (1)$$

Research by Boyd, et. al. [4] showed that with additional performance measurements beyond STC, modified auxiliary equations showed some promise for improved accuracy at low light levels for some module technologies, encouraging a new category of module models that blends the equivalent-circuit and data-driven flavors. Because the IEC-61853 standard requires measurements of P_{mp}, V_{mp}, V_{oc}, and I_{sc} at all the conditions listed in Table I, it provides a basis upon which improved models can be developed.

W/m^2	15°C	25°C	50°C	75°C
1100		x	x	x
1000	x	x	x	x
800	x	x	x	x
600	x	x	x	x
400	x	x	x	
200	x	x	x	
100	x	x		

TABLE I
IEC-61853 MODULE TEST CONDITION MATRIX

In 2014, the authors presented a method to extract 10 parameters for new auxiliary equations using IEC-61853 test data, but the work was limited to cadmium telluride thin-film modules. In this work, we generalize the approach to extend to any module technology type, and demonstrate significant reductions in performance prediction error relative to the 6-parameter single diode model for all 20 modules considered.

II. PROCEDURE

Given P_{mp}, V_{mp}, V_{oc}, and I_{sc} at a given irradiance and temperature condition, four equations can be readily derived from the single diode model at short circuit ($V = 0, I = I_{sc}$), open circuit ($V = V_{oc}, I = 0$), maximum power ($V = V_{mp}, I = I_{mp}$), and the derivative of maximum power $\frac{d(IV)}{dV}|_{mp} = 0$ (see [1] and [2]). These equations can be solved using a nonlinear Newton's method provided that a good estimate of the modified diode non-ideality factor a can be made. Rearranging the equation in the "V_{oc} Method" defined in IEC-60904-9 yields an equation for the diode factor n at any temperature and irradiance, which is related to a by $a = N_s kTn/q$ where N_s is the number of cells in series.

$$n = \frac{(V_{oc} - \beta(T_c - T_{ref}) - V_{oc,ref})}{N_s \cdot V_T \cdot \ln(S/S_{ref})} \qquad (2)$$

The open circuit temperature coefficient β can be recovered directly from the V_{oc} data in the IEC-61853 test matrix at 1000 W/m^2 irradiance.

With an estimate of a at the given condition, the four equations are arranged in the form $\mathbf{F}(\mathbf{x}) = 0$, where $\mathbf{x} =$

$[I_L, I_o, R_s.R_{sh}]'$, where

$$\mathbf{F}=\begin{bmatrix} I_L - I_o\left(\exp\left[\frac{I_{sc}R_s}{a}\right]-1\right) - \frac{I_{sc}R_s}{R_{sh}} - I_{sc} \\ I_L - I_o\left(\exp\left[\frac{V_{oc}}{a}\right]-1\right) - \frac{V_{oc}}{R_{sh}} \\ I_L - I_o\left(\exp\left[\frac{V_{mp}+I_{mp}R_s}{a}\right]-1\right) - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} - I_{mp} \\ I_{mp} - V_{mp}\left[\frac{\frac{I_o}{a}\exp\left[\frac{V_{mp}+I_{mp}R_s}{a}\right]+\frac{1}{R_{sh}}}{1+\frac{I_oR_s}{a}\exp\left[\frac{V_{mp}+I_{mp}R_s}{a}\right]+\frac{R_s}{R_{sh}}}\right] \end{bmatrix} \tag{3}$$

Solving this multidimensional nonlinear equation set yields values for the five single diode model parameters, a, I_L, I_o, R_s, and R_{sh}, at the given condition. This process can then be repeated to calculate the single diode model parameters for each test condition in the IEC-61853 matrix. However, in order to calculate module performance at any irradiance and temperature, a method is needed to estimate the five parameters away from the test condition points.

Previous work in [5] proposed new auxiliary equations that were fitted using a Levenberg-Marquardt method to the parameter maps as a function of irradiance and temperature. While this approach appeared to work nicely for thin-film modules, the forms of the auxiliary equations did not work nearly as well for other module technology types; as shown in Fig. 1, different module types can have quite different parameter surfaces (in shape as well as in magnitude) that make it difficult to assume a single form for a fitting equation. In addition, curve fitting errors sometimes reduced the ability of the model to accurately reproduce test data values in some circumstances.

Instead, to offer a more general procedure applicable to any module type, we apply a Gauss-Markov method for non-gridded data points to interpolate each single diode model parameter directly from the irradiance-temperature solution map. The interpolation reproduces the calculated parameter values accurately at the test data solution points, and does not presuppose a particular response surface for any module. However, for operating conditions near the edge or outside the convex hull defined by the test points, interpolation fails. If the desired operating condition is sufficiently near the edge of the convex hull defined by the irradiance and temperature pairs, the nearest known value is used. Otherwise, if operating condition is too far away, the model reverts to the standard 5 parameter model auxiliary equations as a fallback. While this clearly introduces errors for operating conditions well outside the measured data space, it offers a reasonable compromise on accuracy and general applicability. Of course, the model is not limited to the IEC-61853 test conditions, and so can improve in accuracy as more module performance data is added. Conversely, this approach is general enough if a few points are missing from the full IEC-61853 test matrix, the algorithm will still be able to improve single diode model estimates.

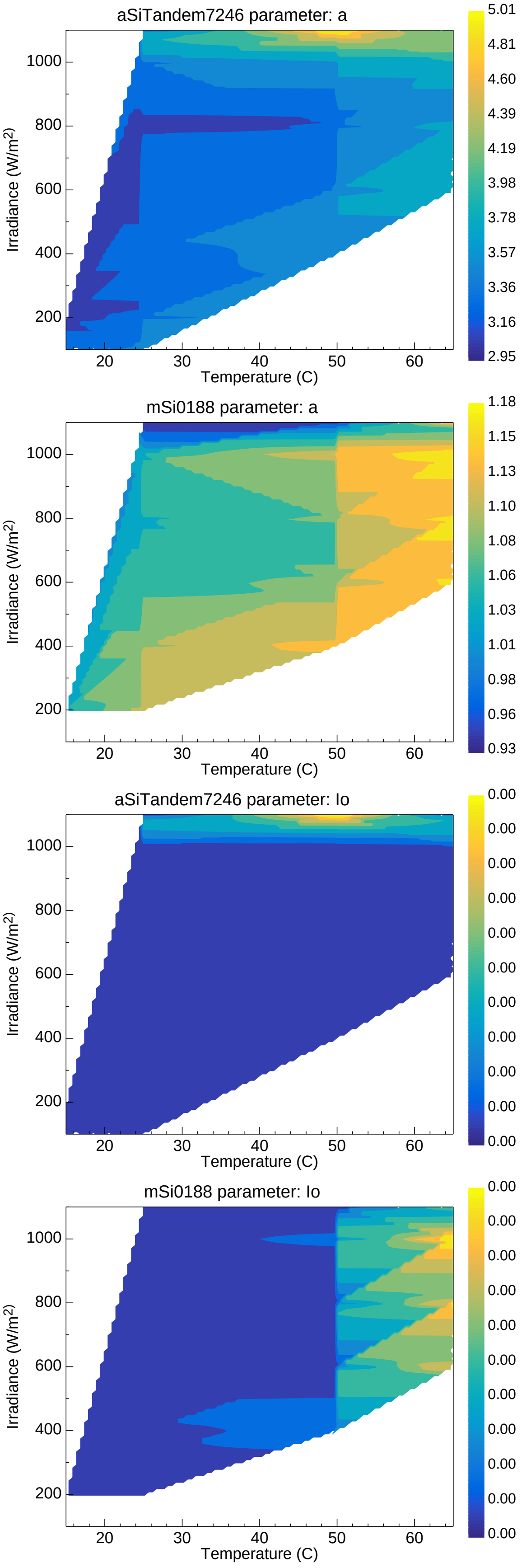

Fig. 1. Behavior of parameters a and I_o as a function of irradiance and temperature for an amorphous silicon module and a polycrystalline module.

III. COMPARISON WITH 6 PARAMETER MODEL

In this section, we qualitatively assess predicted current-voltage (IV) curves at different conditions for two modules. Fig. 2 shows IV curves at 200 W/m^2 and 1000 W/m^2 for a cadmium telluride thin film module and a polycrystalline silicon module. Dotted curves are results from the 6 parameter model, solid lines from this new 61853 model, and points are measured values directly from the IEC-61853 data set. While the 6 parameter single diode model does a good job matching the maximum power point at standard test conditions, the prediction deteriorates at low irradiance levels. Using the calibrated IEC-61853 single diode model significantly improves the prediction accuracy.

IV. ERROR QUANTIFICATION

To begin to quantify the improvement achieved using this new model, we evaluated model accuracy for 20 different modules for which IEC-61853 test data was readily available from [6]. The errors reported in Table II are the irradiance-weighted error between measured MPP power and model-predicted MPP power at all the test conditions. That is, an error at a high irradiance condition is weighted more heavily than at low irradiance. In all cases, the improved IEC-61853 module model reduces errors significantly relative to the 6 parameter single diode model, and on average achieves an 88 % reduction in error across all 20 modules.

Module	6-par. error (%)	New model error (%)	Change (%)
aSiTandem7246	6.80	0.22	-96.7
aSiTandem9031	6.47	0.22	-96.5
aSiTriple28324	7.26	0.75	-89.6
aSiTriple28325	6.70	0.21	-96.9
CdTe75638	5.47	0.24	-95.7
CdTe75669	5.58	0.15	-97.3
CIGS1001	2.69	0.99	-63.1
CIGS39013	10.39	1.87	-82.0
CIGS39017	10.04	2.51	-74.9
CIGS8001	5.01	0.14	-97.3
HIT05662	0.52	0.10	-80.2
HIT05667	0.67	0.08	-88.0
mSi0166	1.83	0.51	-72.3
mSi0188	1.68	0.22	-87.1
mSi0247	1.92	0.21	-89.0
mSi0251	1.92	0.20	-89.5
mSi460A8	1.82	0.17	-90.6
mSi460BB	1.48	0.21	-85.7
xSi11246	0.86	0.04	-95.3
xSi12922	0.57	0.05	-91.3
Average	3.98	0.46	-88.0

TABLE II
IRRADIANCE-WEIGHTED DIFFERENCE BETWEEN MEASURED AND MODELED MPP POWER FOR 20 MODULES.

V. CONCLUSION

This work presents a method for enhancing the single diode PV module performance model using IEC-61853 test data to modify the single diode model parameters at operating conditions other than STC. We show that this model significantly reduces maximum power point prediction errors relative to a standard single diode model approach by 88 % on average across 20 different module types. The procedure will be added to a future version of the publicly available NREL System Advisor Model for general purpose use. Forthcoming work will further quantify how much this model may improve performance predictions by comparing model-predicted power output for these same 20 modules to measured operational data in real world conditions for three locations across the United States.

ACKNOWLEDGMENT

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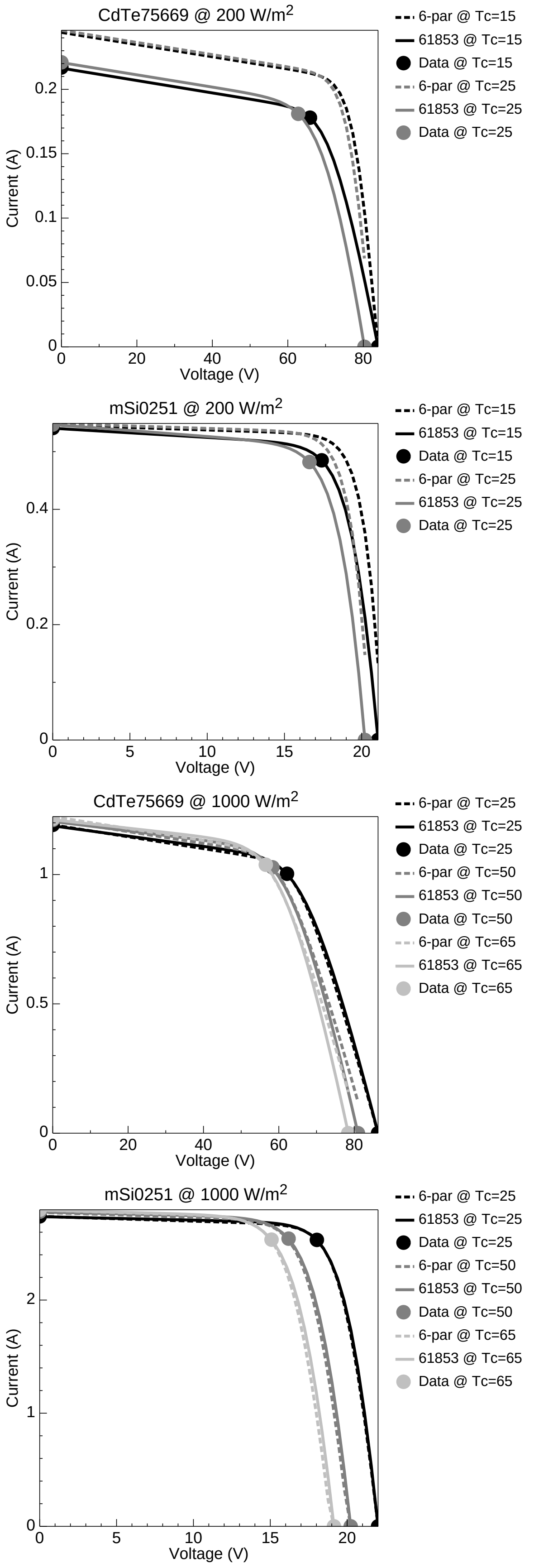

Fig. 2. IV curves for a CdTe and a mSi module as predicted by the 6 parameter and the improved IEC 61853 model.