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Single Diode Parameter Extraction from In-Field Photovoltaic I-V Curves on a Single Board Computer

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***Abstract*—In this paper, we present a new, light-weight approach for extracting the five single diode parameters (I_L, I_o, R_S, R_{SH}, and nN_sV_t) for advanced, in-field monitoring of in situ current and voltage (I-V) tracing devices. The proposed procedure uses individual I-V curves, and does not require the irradiance or module temperature measurement to calculate the parameters. It is suitable for operation on a small, single board computer at the point of I-V curve measurement. This allows for analysis to occur in the field, and eliminates the need to transfer large amounts of data to centralized databases. Observers can receive alerts directly from the in-field devices based on the extraction, and analysis of the commonly used single diode equivalent model parameters. This paper defines the approach and evaluates its accuracy by subjecting it to I-V curves with known parameters. Its performance is defined using actual I-V curves generated from an in situ scanning devices installed within an actual photovoltaic production field. The algorithm is able to operate at a high accuracy for multiple module types and performed well on actual curves extracted in the field.**

***Index Terms*—single diode; pv; single board computer**

I. INTRODUCTION

Advances in I-V curve tracing systems enable in situ scans of strings and modules within production photovoltaic (PV) arrays. For example, devices provided by GroundWorks and Pordis LLC perform I-V curve sweeps by different techniques using a single board computer to store and assess data. Currently, the on-board assessment reports several common I-V features including short circuit current (Isc), open circuit voltage (Voc), dynamic series resistance (Rs), and dynamic shunt resistance (Rsh), where the dynamic resistances are estimated by the linear slope at Voc and Isc, respectively. Measured I-V curves can be accumulated over time, on small, single board computers, to enable more advanced monitoring that can identify fault conditions, e.g., [1].

The algorithm improves on current monitoring practices by reducing measured I-V curves to five parameters which, when trended over time, can illuminate performance problems that are not easily deduced from the I-V curves, e.g. [2]. The method enables PV modelers to improve power predictions by re-calibrating system models with in-field measurements to represent current conditions. Finally, on-board processing of I-V curves reduces the volume of data to be transferred and stored in cases where the raw I-V curve measurements are not of primary interest.

A more detailed understanding of a PV module or string is achieved by comparing measured I-V curves with an equivalent circuit model. This paper presents a light-weight algorithm that extracts parameters for a single diode equivalent circuit model from individual I-V curves. This algorithm works on a single board computer, and its fast run time supports in-line processing as I-V curves are measured. Available in situ I-V curve tracing systems do not include this capability, likely due to the lack of an appropriate extraction method. Available methods [3], [4] may require external measurements such as irradiance or cell temperature, operate on multiple I-V curves, or impose memory or computational demands incompatible with the capabilities of a single board computer.

II. BACKGROUND

Equivalent circuit performance models, such as the single diode model shown in Figure 1, summarize the physical processes of the PV device into an abstract representation consisting of a few electrical circuit elements [5]. By applying

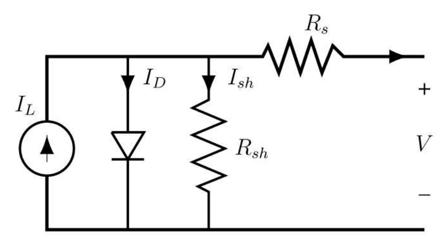

Fig. 1. Single diode equivalent circuit schematic for a photovoltaic device.

Kirchoff's laws and the Shockley diode equation, the single diode equivalent circuit model leads to a mathematical representation for the I-V curve, which is described in Equation 1:

$$I = I_L - I_0\left[\exp\left[\frac{V + IR_S}{nN_sV_t}\right] - 1\right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where I is the current, V is the voltage, I_L is the light current, I_0 is the diode reverse saturation current, R_S is the series resistance, R_{SH} is the shunt resistance, n is the diode ideality factor, N_s is the number of cells in series, and V_t is the diode thermal voltage [6] calculated from the cell temperature. The single diode equation thus requires five parameters that are specific to each PV module: I_L, I_0, R_S, R_{SH}, and n.

Literature provides hundreds of reported methods for the extraction of single diode model parameters; see [7], [8], [9] for surveys. For example, some methods use only the specification sheet values to define the model parameters [10], [3]. Others employ sophisticated optimization approaches such as genetic algorithm [11] and differential evolution [12] techniques. Current literature does not report a parameter

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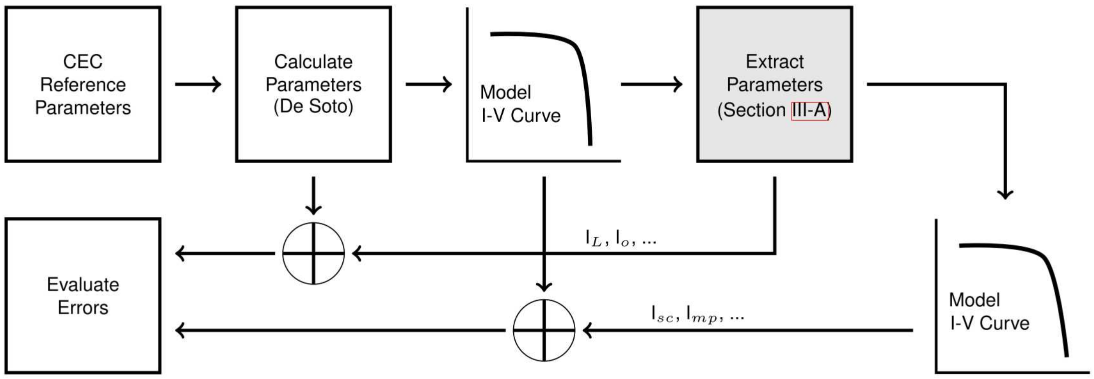


Fig. 2. The algorithm's accuracy is evaluated by computing I-V curves using known parameter values, extracting parameters from the computed I-V curves, and comparing the extracted values with the known values to determine errors.

extraction method that can operate on a single board computer and evaluate I-V curves at the point of measurement. Some simple techniques could be considered, e.g., [13], but many available methods employ iterative calculations or multivariate optimization processes that may exceed computing resources or operate too slowly to process I-V curve measurements in near real-time at the point of measurement in the field.

III. Methodology

We describe an algorithm that can extract single diode model parameters from a I-V curve measured by an in situ monitoring system on a single board computer. We verify the algorithm's accuracy by applying it to recover known parameters from calculated I-V curves. We use the algorithm on a single board I-V curve tracer and show the algorithm's performance for measured I-V curves.

A. Parameter Extraction Algorithm

The lightweight parameter estimation process obtains the following quantities in Equation 1: I_L, I_0, R_S, R_{SH} and $nNsVth$ (the diode quality factor n is obtained from $nNsVth$ if cell temperature is knwon). The approach extracts the parameters for each I-V curve. First Equation 1 is simplified as shown in Equation 2 by eliminating the "-1", which has negligible effect on the I-V curve shape:

$$I = I_L - I_0\left[\exp\left[\frac{V + IR_s}{nN_sV_t}\right]\right] - \frac{V + IR_s}{R_{SH}} \qquad (2)$$

Equation 2 is then rearranged into a linear and an exponential component as indicated in Equation 3:

$$I \approx \frac{I_L}{1 + G_pR_s} - \frac{G_pV}{1 + G_pR_s} - \frac{I_0}{1 + G_pR_s}\exp\left[\frac{V + IR_s}{nN_sV_{th}}\right] \qquad (3)$$

where the shunt resistance R_{SH} is replaced by the shunt conductance $G_p = \frac{1}{R_{SH}}$. Then, the two coefficients in the linear component are estimated using linear least-squares regression over a portion of the I-V curve $0 \leq V \leq V_L$ as shown in Equation 4.

$$I \approx \frac{I_L}{1 + G_pR_s} - \frac{G_p}{1 + G_pR_s}V = \beta_0 + \beta_1 V \qquad (4)$$

Initially, $V_L = \frac{V_{OC}}{3}$; if $\beta_1 \geq 0$ (due to noise in the measured current), V_L is increased to add additional data points until $\beta_1 < 0$ is obtained. The right-hand side of Equation 4 is substituted into Equation 3 and the result rearranged to obtain:

$$\log(\beta_0 - \beta_1 V - I) = \log\left[\frac{I_0}{1 + G_pR_s}\right] + \frac{1}{a}V + \frac{R_s}{a}I = \beta_2 + \beta_3 V + \beta_4 I \qquad (5)$$

For $I \geq 0.1 I_{SC}$ values for β_2, β_3, β_4 are obtained by least-squares regression, and four of the single diode parameters are calculated sequentially from the regression coefficients:

$$R_S = \frac{\beta_4}{\beta_3} \qquad G_p = \frac{\beta_1}{1 - R_S\beta_1}$$

$$R_{SH} = \frac{1}{G_p} \qquad I_L = (1 + G_pR_S)\beta_0$$

Finally, the four known parameters are used in Equation 3 at (V_{MP}, I_{MP}) to calculate a value $I_{0,MP}$, and at $(V_{OC}, 0)$ to obtain $I_{0,OC}$, and I_0 is obtained by the following rules:

1) if $I_{0,MP} > 0$ and $I_{0,OC} > 0$ then $I_0 = \frac{I_{0,MP} + I_{0,OC}}{2}$
2) if $I_{0,MP} > 0$ and $I_{0,OC} \leq 0$ then $I_0 = I_{0,MP}$
3) if $I_{0,MP} \leq 0$ and $I_{0,OC} > 0$ then $I_0 = I_{0,OC}$
4) else I_0 is undefined and the fitting is judged to fail.

The parameter extraction method is formulated to avoid iterative numerical optimization, and so that regressions are well-conditioned (i.e., lines are fitted through data with nearly linear features and relatively shallow slope). Code for the fitting is available in pvlib python [14].

B. Evaluate Accuracy

We evaluate the accuracy of the proposed procedure by comparing the extracted parameters (i.e. I_L, I_0, etc.) and the I-V curves computed using the extracted parameters with the known values as illustrated in Figure 2. A random selection

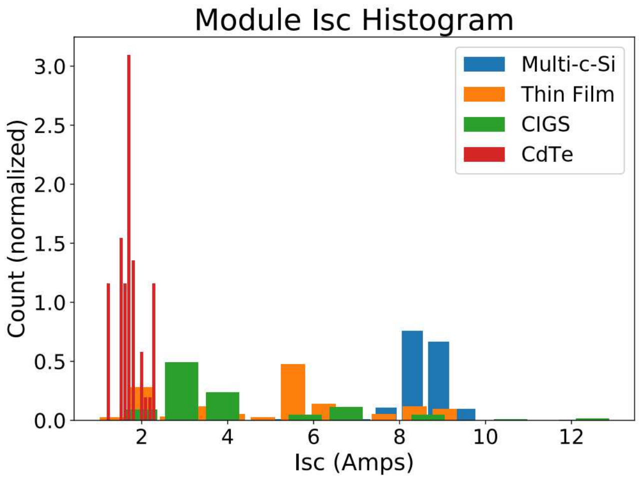


Fig. 3. The four modules had varying short circuit current ratings that ranged from 1.5 to 10 amps.

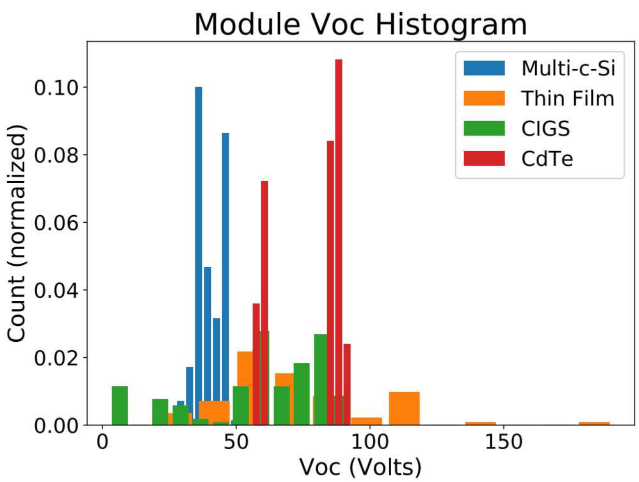


Fig. 4. The open circuit voltage for each of the modules ranged from 10 to over 150 volts.

of 512 modules (104 multi-crystalline silicon (multi-c-Si), 216 thin film, 138 copper indium gallium selenide (CIGS), and 54 cadmium telluride (CdTe)) are obtained from the System Advisor Model (SAM) database [15], which provides parameters for the model described by De Soto et *al.* [6]. The distributions of I_{sc} and V_{oc} for the test modules are plotted in Figures 3 and 4. The multi-c-Si modules have the highest I_{sc} followed by thin film, CIGS and CdTe. The CdTe modules have the largest V_{oc} followed by CIGS, thin film, and multi-c-Si with the smallest V_{oc}.

For each of these modules, the I-V curves are calculated at different irradiance (300, 600, 800, 1000, and 1200W/m^2) and cell temperature (20, 30, 40, 50, 60°C) conditions. Parameters are then extracted from each of the computed I-V curves using the proposed methodology (Section III-A) and I-V curves are calculated with the extracted parameters; the known and extracted parameters, and input and output I-V curve characteristics are compared to determine the procedure's accuracy.

C. Analyze Performance

The algorithm's performance is first evaluated by it's ability to produce parameters that yield calculated I-V curves which correspond well with I-V curves measured in the field. The measurements are from I-V scans performed on 12 multi-c-Si modules installed in a production field. The majority of the I-V curves are measured during conditions that produce I_{sc} and V_{oc} values around 7 Amps and 41 Volts respectively as illustrated in Figures 5 and 6; each I-V curve comprises 100 to 140 points (i.e. current and voltage pairs). The proposed procedure is applied to extract parameters from each I-V curve. Extracted parameters are used in the single diode equation to calculate an I-V curve. The algorithm's performance is reasonable if the errors in the modeled maximum power point are similar to measurement error, i.e., below 0.5%.

We also examined the algorithm's capability to produce a single diode performance module from I-V curves measured in situ. We consider the single diode model in [6] which requires seven parameters at reference conditions: the five parameters for the single diode equation (Eqn. 1), the energy bandgap

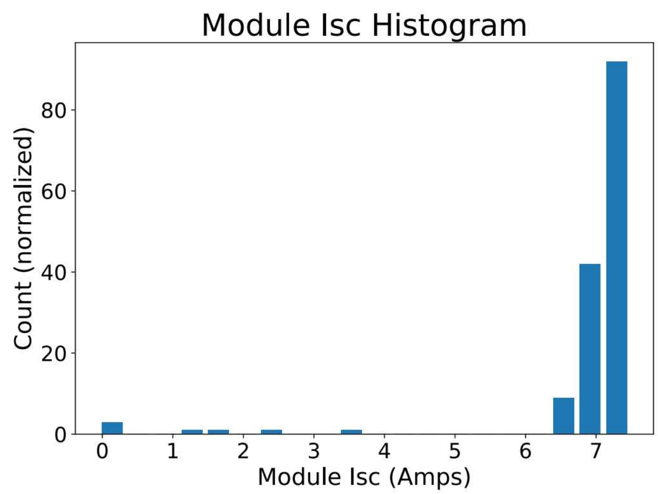


Fig. 5. Majority of the measured I-V curves have an I_{sc} value close to 7A.

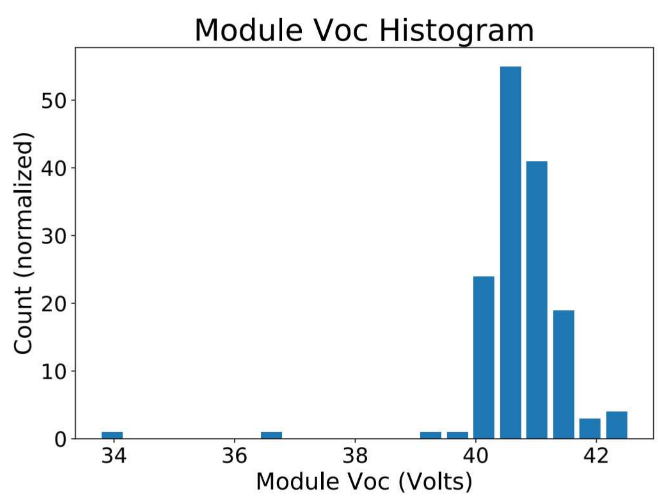
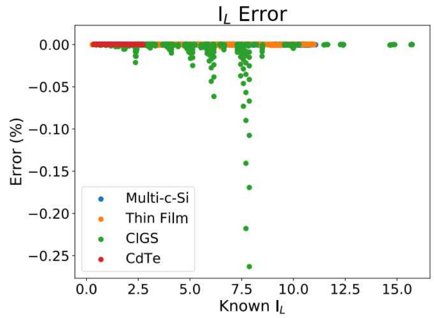
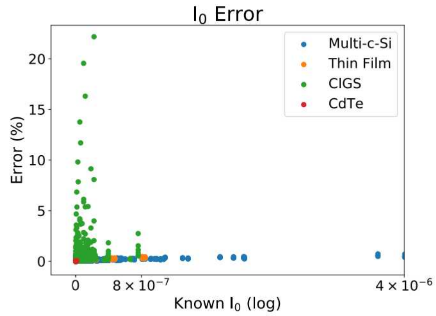


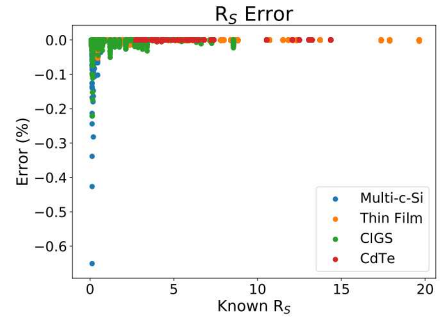
Fig. 6. The majority of the I-V curves have a Voc between 40 and 42 volts.



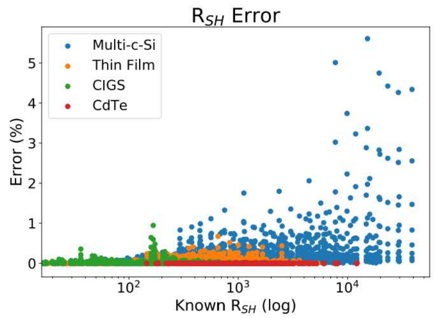
(a) Parameter IL Error



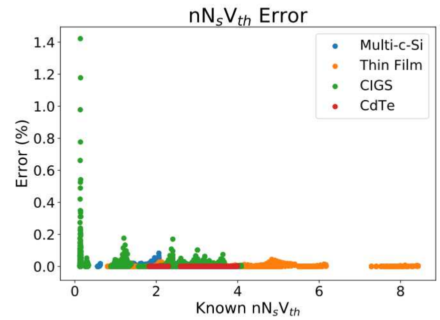
(b) Parameter I0 Error



(c) Parameter Rs Error



(d) Parameter Rsh Error



(e) Parameter nN_sV_{th} Error

Fig. 7. The parameter extraction method recovered the five single diode parameters with low errors for a random sample of 512 modules of four types.

and the temperature coefficient of short-circuit current. The seven parameters are used in a set of equations to calculate the five values for Eqn. 1 at any irradiance and temperature condition, then the I-V curve is computed. We set the energy bandgap and temperature coefficient to values representative for the multi-c-Si modules. We define reference conditions using in-field measurements of irradiance and temperature and use the corresponding measured I-V curve to determine the other five model parameters. We then apply the performance model at measured irradiance and temperature conditions, and compare the modeled I-V curve characteristics (i.e. I_{sc}, V_{oc}, etc.) to the corresponding measurements.

IV. Results

The algorithm's accuracy is determined by the procedure described in Section IV-A and the algorithm's performance is quantified as described in Section IV-B.

A. Accuracy

The differences between the known and extracted single diode parameters are small for all modules as illustrated in Figure 7. For the I_L parameter with known values ranging between 0 and 16 as shown in Figure 7(a), the error is close to zero for the multi-c-Si, thin film, and CdTe modules, and the largest error of -0.25% occurs for a CIGS module with a known I_L of about 7.5. The I_0 errors for multi-c-Si, thin film, and CdTe are very low, while error exceeds 2% for some CIGS modules. The R_s parameter errors are less than -1% for all modules. The R_{SH} errors remain below 1% except for the some of the multi-c-Si modules. Finally, the nN_sV_{th} errors, shown in Figure 7(e), are mostly below 0.2%, with error reaching 1.4% for some CIGS modules.

The errors associated with the extracted parameters did not translate to significant deviations between the input I-V curves and I-V curves calculated with the extracted parameters. Errors in I_{sc} and V_{oc} are less than 0.01%, while errors in maximum power point current and voltage are less than 0.2% for all modules. Moreover, error in the maximum power is below 0.005%, with the exception of one outlier, as shown in Figure 8.

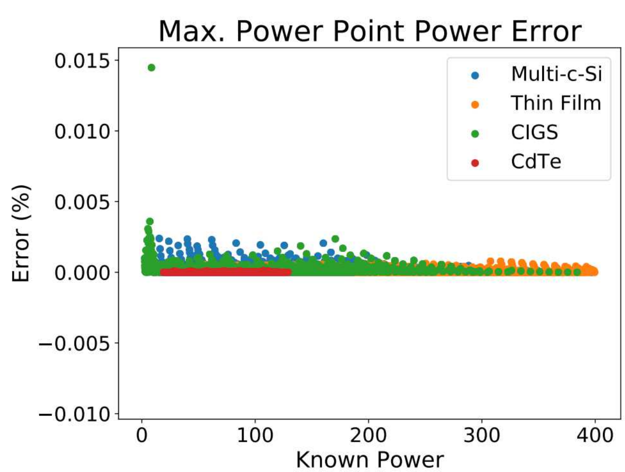


Fig. 8. The maximum power point power errors for the models that use the extracted parameters are below 0.005% for each of the four module technologies.

B. Performance

The proposed method successfully reproduces I-V curves measured in the field. The errors associated with I_{mp}, V_{mp}, I_{sc}, and V_{oc} are all between -2 and 2% as shown in Figure 9 and 10. The V_{oc} and I_{sc} errors are very small and exhibit a small amount of small bias. The voltage and current at maximum power point, on the other hand, are more scattered, but seem to be centered around zero.

The proposed method also successfully produced a performance model for the multi-c-Si modules. We set reference conditions to a plane of array irradiance of 815W/m^2 and a back-of-module temperature of 46°C. The SAM database provides a short-circuit temperature coefficient for a module similar to the multi-c-Si modules. De Soto et al. [6] provides an energy bandgap value of 1.121eV for silicon cells, and a temperature coefficient for the energy bandgap of -0.0002677 °C^{-1}. The five parameters for the single diode equation (Eqn. 1) are obtained at reference conditions by applying the parameter estimation method to the I-V curve measured at those conditions.

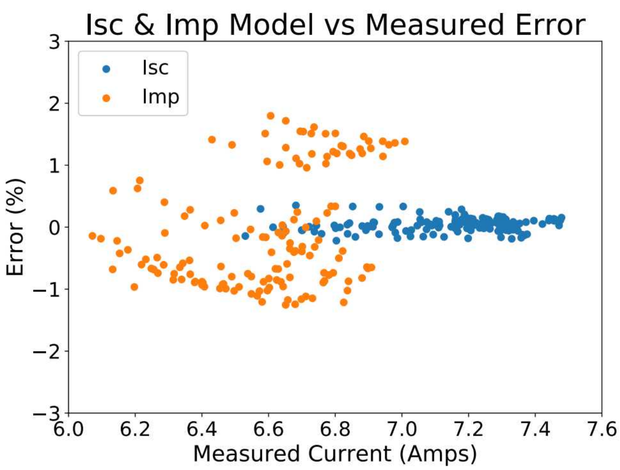


Fig. 9. The I_{sc} error is very small, while the I_{mp} error is more scattered for measured current between 6 and 7.6 amps.

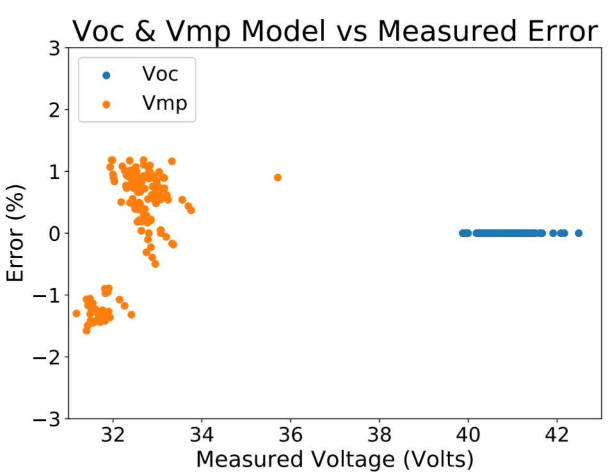


Fig. 10. The errors associated with the V_{oc} model are vary small, and the V_{mp} are more scattered but less than 2%.

The performance model using parameters derived from in situ measurements is generally successful at describing the multi-c-Si we measured. The same multi-c-Si module is listed in the CEC database, thus a performance model is also available, derived from laboratory measurements of a module of the same manufacture using the procedure in [3]. Figure 11 compares a measured I-V curve, an I-V curve calculated using the SAM database parameters, and an I-V curve computed using the parameters extracted in-field using the proposed procedure. The I-V curve resulting from the in-field extraction method resembles the actual I-V curve well, especially at V_{oc}. However, the two modeled I_{sc} values show similar differences from the measured value.

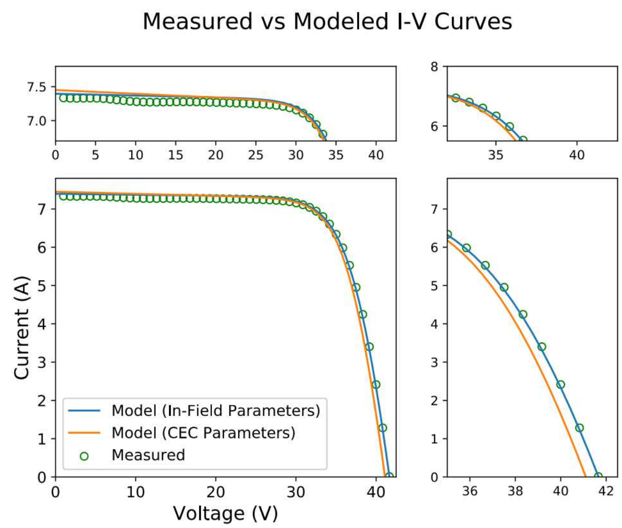


Fig. 11. The two models resembled the in-field I-V curves well. The model that used the parameters extracted from the actual curves produced more accurate results, especially close to V_{oc} and I_{sc}.

The two models, that either use the SAM parameters or the in-field extracted parameters are applied over a small range of irradiance and temperature conditions and compared as shown in Figures 12 and 13. Figure 12 plots I_{sc} and I_{mp} for each model versus the measured. The plots indicate a strong linear relationship between the two models and the actual measurements. And, the model that incorporates the CEC parameters has a slight bias. The modeled V_{mp}, shown in Figure 13, has a strong linear relationship, while the V_{oc} did not match as well. In this situation, the single diode model that uses the CEC parameters as a reference tended to under estimate and the model that used parameters extracted using the proposed methodology ended up creating more accurate outputs.

V. Conclusion

The extraction of single diode parameters from in-field I-V curves using the light-weight methodology provides accurate results at a low cost. The algorithm can easily run on a small, single board computer out in the field and generate parameters that can be stored and shared; it eliminates the need for the storage and transfer of large data sets that include the entire I-V curve. In addition, the approach provides parameters that accurately characterize modules and can improve the accuracy of models.

The evaluation of the proposed extraction method showed that the calculated parameters resembled the known parameters well for the Multi-c-Si, Thin Film, and CdTe modules. The approach did not work as well on CIGS modules, that had low I_{sc} and high V_{oc}. The evaluation of the proposed parameter extraction approach and the standard CEC database parameters revealed some improvements in the bias error for I_{sc} and high V_{oc}. The results showed that the proposed methodology can provide reliable single diode parameters using in situ I-V curve tracing systems and improve the overall monitoring of PV arrays.

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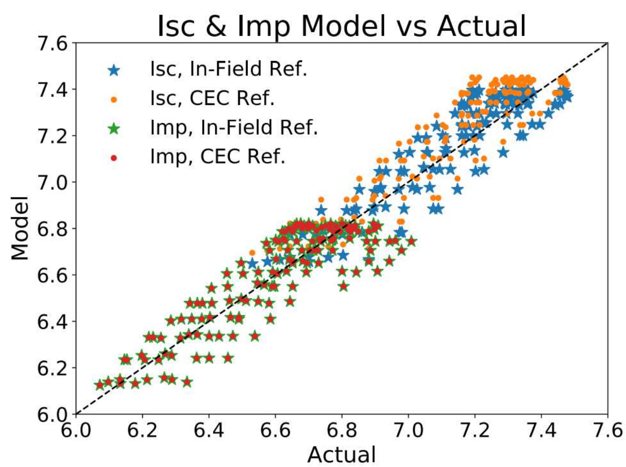

Fig. 12. The I_{sc} and I_{mp} results from each of the modeling approaches generate similar results. The model that used the CEC parameters tended to over estimate the I_{sc} value in comparison with the proposed approach.

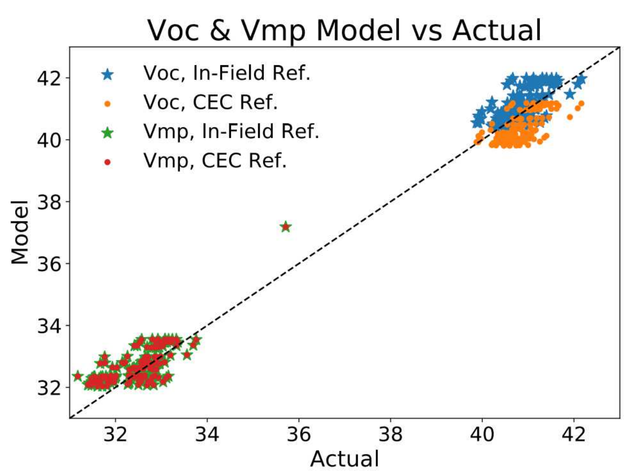

Fig. 13. The predictions of the V_{mp} are very similar for the two approaches. The model that uses the CEC parameters, however, underpredicted V_{oc}.

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