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Quantify PV Module Degradation based on Model Coefficients Extracted from an Embedded Data Acquisition Devices

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***Abstract*—Photovoltaic investments demand that reasonable power is produced for 20 or more years. However, module level degradation can occur in many different forms. This paper evaluates modules within a grid connected array using embedded I-V tracing devices. The I-V curves where evaluated on a weekly basis using the Sandia Array Performance Model and the Loss Factor Model coefficients and parameters. The intent is to identify common degradation modes and the associated parameters to monitor. The initial results described in this abstract were not conclusive because the data set was too small. The final paper will report on the analysis of thousands of curves collected over multiple years in many different climates.**

***Index Terms*—photovoltaic degradation**

I. Introduction

Financial investment opportunities in solar photovoltaic (PV) systems depend on long-term operations. The systems are expected to produce power for 20 plus years. Unfortunately, solar PV modules can degrade and cause power production losses. The losses can be caused by degradation in the packaging material, adhesive losses, interconnection failures, moisture intrusion, and semiconductor device corrosion [1]. The rate at which the module degrades can depend on the climate and module type.

Researchers have been investigating degradation rates for many years. The rates have been calculated based on various metrics that include I-V characterization, regression modeling, and normalized ratings [2]. The characterization of I-V curves provides detailed information regarding the relationship between the current and voltage for the semiconductor device. Often I-V curves are obtained periodically to evaluate degradations. For example, Reis et *al.* compared the performance of PV modules over an 11 year gap and showed that the max power was reduced by about 4% [3]. Other studies have evaluated outdoor PV modules at more regular intervals.

Outdoor PV module evaluations have provided degradation information for PV technologies such as silicon, CdTe, and CIGS. In one study, the average degradation rate for 40 different modules from 10 different manufactures was calculated to be 0.7%/year based on continuous data [4]. I-V curve characteristics, such as short circuit current, open circuit voltage, and fill factor, provide detailed information that can highlight the the cause. For example, Smith et *al.* found that larger max power degradation was caused by large fill factor losses while the open circuit voltage had small losses [5]. Continuous, near real-time module or string level I-V curves can provide valuable insight into module degradation for different climate zones, seasons, and module types.

The present work collected module level I-V curves continuously throughout the day and year. I-V curves were taken at various temperatures and irradiance levels and stored in a large database. The current and voltage values were then used to extract necessary coefficients to run the Sandia Array Performance Model (SAPM. The data was also used to calculate the Loss Factor Model (LFM) parameters [6]. The parameters when then used to monitor and evaluate factors causing the PV module's power output to degrade. The initial test used a small set of data. The full paper will use thousands of curves extracted from actual modules over multiple years.

II. Methodology

Accurate I-V curves at the module level provide detailed performance information. Critical information from an I-V curvesdescribe the open circuit voltage, short circuit current, maximum power point voltage and current, and series and shunt resistance. The intent of this work is to evaluate degradation based on the continuous extraction of I-V curve features. These features include SAPM coefficients and LFM parameters. The SAPM coefficients will be used to produce reference I-V curves points. The calculated reference values will then be compared with the measured value. The comparison will be conducted on a weekly basis. The LFM parameters will be used to identify the cause for loss in maximum power. Initial results are presented in this abstract and the final paper will include an evaluation based on thousands of I-V curves measured over many years.

A. I-V Curve Data

There are various ways to obtain I-V curves from PV modules [7]. New technologies allow for I-V curve traces to be measured in-situ with the PV array. Pordis LLC offers a I-V tracer that scans the PV system at a string level. Module level I-V traces can be conducted using a product made by Stratasense LLC [8]. The Stratasense device, shown in Figure 1 is able to remove the individual panel from the string, perform a sweep, and then return the module back to the string.

The initial tests used I-V curve data extracted from a 10.8kW array in Albuquerque, New Mexico. The complete conference paper will include thousands of I-V traces from around the world. The traces will also span multiple years to provide a detailed analysis of degradation over time. It will also consider the impact of climate zones. This data is currently being stored in a non-relational data warehouse at

Fig. 1. Module level I-V curves where extracted from the module within the PV array using an in situ device. The device was controlled wirelessly and performed an I-V trace by extracting the module from the string. When it was finished it returned the module back into the string.

Case Western Reserve University and will be accessed using the analytical environment known as Energy-CRADLE [9].

B. SAPM Reference Model vs Measured

The SAPM defines basic equations for current, voltage, and power. The equations are based on coefficients and parameters that include the diode factor, voltage and current temperature coefficients, effective irradiance, and other empirically derived terms. The proposed approach assumes that the temperature coefficients do not change and calculates the reference value at standard operating conditions (1000W/m^2 and T_m=25°) for I_{sc}, I_{mp}, V_{oc}, and V_{mp}. For example, King et *al.* defined Equation 1 and 2 for reference short circuit current and open circuit voltage [10].

$$I_{sco} = I_{sc}/[E_e(1 + \alpha_{Isc}(T_m - T_o))] \quad (1)$$

$$V_{oco} = V_{oc} - N_s\delta(T_m)ln(E_e) - \beta_{Voc}(E_e)(T_m - T_o) \quad (2)$$

The present work calculated the ratio between the derived reference value and the module manufacturer reference value described in the specification sheet. This ratio for I_{sc} and V_{oc} are shown in Equation 3:

$$I_{Ratio} = \frac{I_{sco}}{I_{sco,spec}},\ V_{Ratio} = \frac{V_{oco}}{V_{oco,spec}} \quad (3)$$

This ratio will also be applied to I_{mp} and V_{mp}.

C. Loss Factor Model Parameters

The LFM parameters can be extracted from outdoor I-V curves as shown in Figure 2. The parameters can be used to analyze performance and define the reason for reduced power [11]. The parameters, defined in Equations 4 to 9,

$$nIscT = \frac{mIsc}{rIsc}/E_e \text{ x } T_{corr,Isc} \quad (4)$$

$$nRsc = \frac{mIr}{mIsc} \quad (5)$$

$$nImp = \frac{mImp}{mIr}\frac{rIsc}{rImp} \quad (6)$$

$$nImp = \frac{mVmp}{mVr}\frac{rVoc}{rVmp} \quad (7)$$

$$nRcc = \frac{mVr}{mVoc} \quad (8)$$

$$nVocT = \frac{mVoc}{rVoc} \text{ x } T_{corr,Voc} \quad (9)$$

where $T_{corr,Voc}$ = 1 + β_{Vmp}(25-T_m) and $T_{corr,Isc}$ = 1 + α_{Imp}(25-T_m), and E_e is the plane-of-array irradiance, were calculated for each curve within three different irradiance bins. The irradiance bins were set to plus or minus 2% of 200, 600, and 1,000W/m^2. The average value for each of the parameters was then calculated over a one week period.

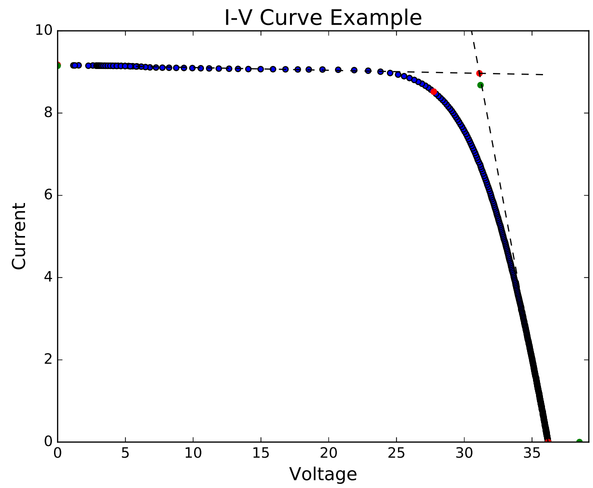

Fig. 2. The Loss Factor Model parameters where extracted from each I-V curve. This required the calculation of the reference STC and an extraction of the measured values.

III. Results

A. SAPM Reference Model

The initial short circuit current results for the comparison of the SAPM reference values and the module specifications are shown in Figure 3. The analysis considered the ratio for three different irradiance conditions over a 10 week period.

The results do not indicate any losses caused by module degradation. The final paper will apply this methodology to a much larger data set and report detailed findings associated with this SAPM comparison methodology.

B. LFM Parameters

The I-V curves extracted from modules in the 10.8kW were used to find the six LFM parameters. Figure 4 shows that the LFM parameters followed reasonable patterns. However, there was scattered results for nImp and nRsc at lower irradiance levels. The six LFM values were analyzed over a 11 week period to identify potential degradation.

The degradation analysis considered the average LFM value at 1000W/m^2. The averaged value was computed for a one week period and plotted in Figure 5. The initial results did

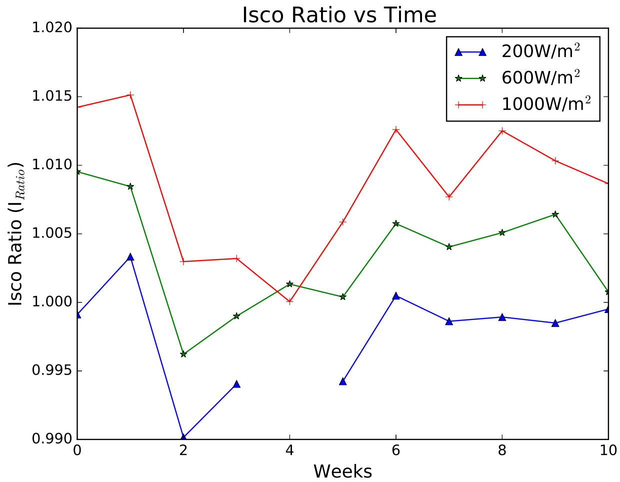

Fig. 3. The initial results for the I_{sco} ratio did not show degradation. The short time frame, of 10 weeks, did not provide enough time for the PV modules to degrade. The final report will include results from a much larger data set.

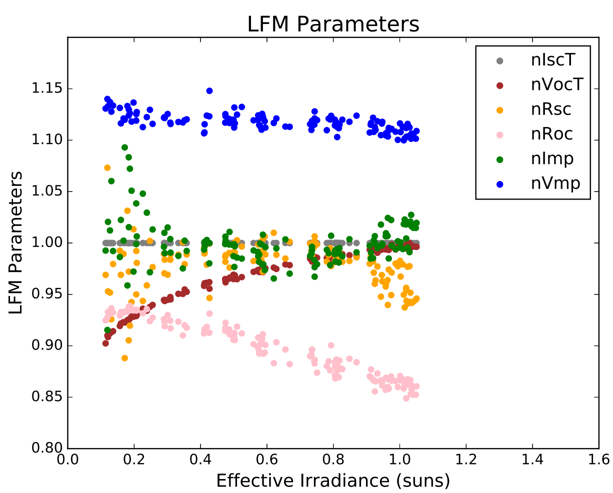

Fig. 4. The LFM parameters as a function of effective irradiance for the 11 week initial analysis period. More data will be analyzed for the full paper.

not show any degradation for the 11 week period. The final paper will include a more detailed analysis of thousands of I-V curves.

IV. Conclusion

The present extracted I-V curve data from individual modules using an embedded curve tracing device. The curves were used to extract SAPM and LFM coefficients and parameters. The values were evaluated over time to analyze module degradation. The initial results were for a small data set and showed now degradation over a 10 week period. The final paper will evaluate more curves over a larger time period.

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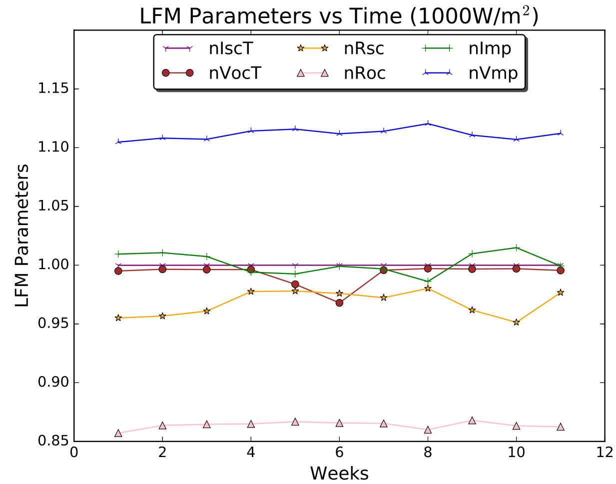

Fig. 5. The LFM parameters averged over a one week period for 11 weeks did not show signs of degradation. The final paper will apply this methodology to a more significant data set.

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