COMPARATIVE STUDY OF THE PERFORMANCE OF FIELD-AGED PHOTOVOLTAIC MODULES LOCATED IN A HOT AND HUMID ENVIRONMENT

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Abstract -- **Long-term monitoring of systems installed in the field is the ultimate standard for evaluating photovoltaic components and systems. This study, which involves the long-term outdoor exposure in a hot and humid climate, intends to address the performance degradation and failure mechanisms which are difficult or impossible to simulate in the lab during time constrained accelerated tests. Experimental data including irradiance, temperature, DC/AC current and voltage has been collected on diverse generations of photovoltaic modules installed throughout the state of Florida. Long term module reliability and lifetime are evaluated using a two pronged approach. 1) Modules have been deployed outdoors for long time periods with systematic - 15 minutes interval- climatic and performance measurements 2) Real–time climatic and performance measurements of modules following long-term outdoor exposed. Visual, IR and electrical insulation inspections were performed are also presented in this paper. Multiple analytical methods are used to quantify energy production and power degradation over time, including Performance Ratio analysis, and PVUSA regression analysis. Real-time field measurements were reviewed for both overall return rates and compare them with the nameplate performance values and to identify the failure mechanism that caused the return.**

Index Terms —Photovoltaic, reliability, degradation rate, Performance Rati, PVUSA regression

I. INTRODUCTION

Developing clean and renewable energy has become one of the most important tasks assigned to modern science and engineering. Photovoltaic (PV) energy looks to be a very promising future energy resource as it is pollution free and abundantly available anywhere in the world. It is cost effective for remote applications where utility power is unavailable, and in many parts of the world, it is becoming cost - competitive with traditional sources of utility power (e.g. Germany, Japan, California). It is important to conduct accurate and dependable studies of PV system performance for the future development of these systems. For different manufacturers, analysis and performance assessment is a benchmark of quality for existing products and a help to reevaluate product warranty and long term performance. For the research and development community (R&D), these studies are an aid to identify future needs. Finally, for system integrators and end-users, they are a guide to evaluate product quality and a help in decision making. However, in the past, less effort has been placed to validate models using PV systems installed in the hot and humid field over long periods of time. The performance characteristics of PV modules are needed in order to model their annual performance [1]-[3].

As the industry grows, a clear need is raising for greater education about appropriate industry standard performance parameters for PV systems. Performance parameters allow for the detection of operational problems, facilitate the comparison of systems that may differ with respect to design, technology, or geographical location, and validate models for system performance estimation during the design phase. Industry wide use of standard performance parameters and system ratings will assist investors in evaluating different proposals and technologies, giving them greater confidence in their own ability to procure and maintain reliable, high quality technologies. Standard methods of evaluation and rating will also help to set appropriate expectations for performance with educated customers, ultimately leading to increased credibility for the PV industry and positioning it for further growth.

Module degradation and failure is often present in PV systems but not immediately recognized. System design can frequently mask the effects of module performance degradation and/or individual module failures. On the other hand, some module degradation mechanisms can significantly degrade the operation and/or performance of the entire system. This is why identifying degradation mechanisms and establishing degradation rates has become significantly important in this industry. Information on system performance at different locations has been remotely collected since the 1990's at the Florida Solar Energy Center (FSEC). However, lack of support has impeded coordination of such data, resulting in minimal data being generated with varied measurement

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techniques and analytical methods. Therefore, there is opportunity to better utilize this data toward understanding degradation rates and PV performance.

FSEC has been highly involved in testing both commercially available PV modules as well as prototypes not yet ready for industry. The testing here consists of indoor module tests performed with a solar flash simulator, which allows for highly repeatable experiments, as well as outdoor testing performed with highly sensitive measurement instrumentation.

Using decades of experience in photovoltaic research development, design, testing and applications, FSEC reviews each PV system design for compliance with the National Electrical Code (NEC) and the appropriate use of accepted design practices [4]. Not only module testing and research is performed at the Florida Solar Energy Center. FSEC has also partnered with Sandia National Laboratories (SNL), the Southwest Technical Development Institute (SWTDI), and the California Energy Commissions Public Interest Energy Research (CECPIER) to characterize the performance of PV inverters operating over extended periods of time [5].

II. EXPERIMENT

Since the 1990's the Florida Solar Energy Center has been collecting data from different PV sites in the state of Florida, including schools, houses and universities, among others. With over 150 systems listed in the FSEC PV system database (fig.1), 70 of which have performance data, there is clearly a rich history of archived data which can be used to better understand and quantify the long-term performance of PV modules and systems. DC operating current, DC operating voltage, and AC power were recorded for extended periods of time (greater than 3 years), along with environmental conditions like plane-of-array (POA) irradiance, module temperature, and ambient temperature. For years, these sites have been contributing with valuable data that today can be used to study degradation rates, performance, and service lifetime of different field-aged PV technologies.

As the PV systems are installed, sensors and transducers that measure data every second, such as irradiance, voltage, current, power and temperature are also installed. Measured data is collected by the data logger and sent over an Internet connection to FSEC's servers. This data collected is then averaged to create fifteen minute averages data points that are later used for different type of analyses. Figure 2 below presents a flow chart of the data collection process.

Fig. 1 The location of the PV systems installed in Florida. Insert: the red dots represent the systems analyzed in this study

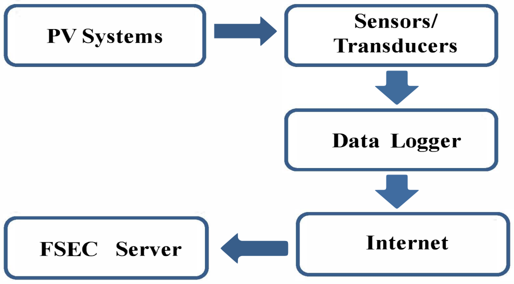

Fig 2. Data Set Construction Flow Diagram

The energy produced by a grid connected photovoltaic system depends on climatic factors, mainly the incident radiation on the modules and the temperature of work of such, which is function mainly of the radiation and the ambient temperature [6]. For every system monitored and that FSEC has collected data, this important meteorological information has also been recorded and will later be used to analyze the performance and the degradation of the systems studied.

Five systems in the state of Florida have been selected to perform the degradation studies presented. Table 1 shows general system information for each of the five selected systems. Plotting the collected parameters versus time is a good way to spot obvious errors in data collection. (Figure 3 and 4)

System	Size (W)	Technology	Install Date	Years	Azimuth & Tilt
CEL	3960	p-Si	12/8/03	3	225° West of South; 15°
FAM	5940	p-Si	12/15/03	5	208° West of South; 25°
KMS	1980	m-Si	1/15/04	4	180° South; 17°
MMS	3960	p-Si	2/5/03	4.5	180° South; 25°
WFH	3960	p-Si	9/5/03	2.5	180° South; 22.5°

Table 1 General System Information

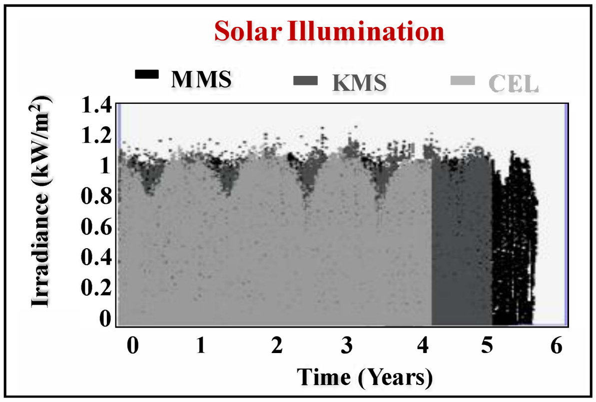

Fig. 3 Irradiance as a function of time raw data for three of the five systems that were used for this study.

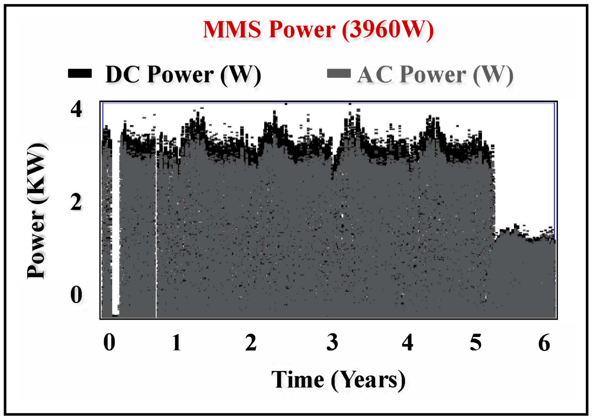

Fig. 4 Power output DC-AC as a function of time raw data for one of the five systems that were used for this study.

After the collected data from the different FSEC monitored PV sites is retrieved, we perform the filtering process. As mentioned before, not all the data acquired is valid since network failures can cause data not to be stored properly, therefore this kind of data is filtered out. When filtering the data only valid data is kept, making the analysis easier and eliminating errors. Of course, some problems are present when filtering the data too much, especially when filtering irradiance in the 800-1200 W/m^2 in months like November, December and January. Once the data sets are filtered, two sets are obtained for different irradiance ranges and a constant range for ambient temperature, followed by two distinctive analysis methods. Figure 5 shoes the data selection flow diagram.

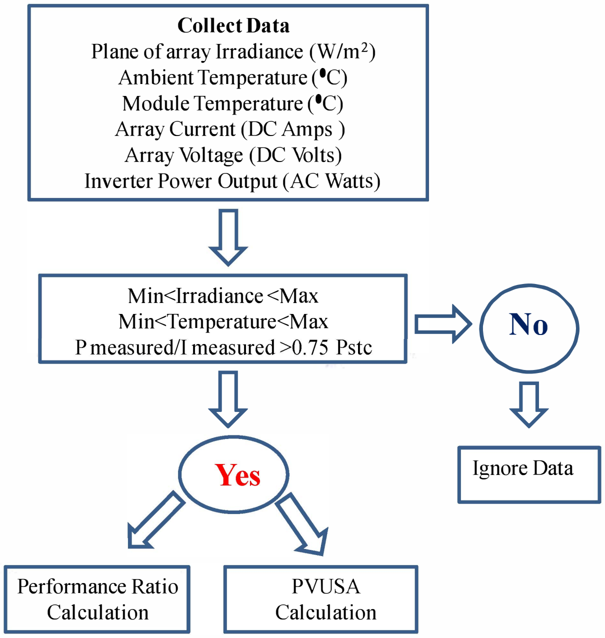

Fig. 5 Data Selection Flow Diagram

III. RESULTS AND DISCUSSION

Throughout the years, researchers and developers alongside with industry and manufacturers have come up with different type of analyses to better qualify and quantify degradations rates and estimate service time of field aged PV modules. Two widely accepted analyses, the Performance Ratio analysis the PVUSA Regression, are to be examined and compared in order to find acceptable degradation rates for different PV modules installed.[7]-[10] The total amount of incident irradiance has been filtered in two ranges, with the purpose of examining the degradation of the systems at these two windows of irradiance. Table 2 and 3 below show the results obtained by performing each of these analyses on the collected data. Such results are obtained by means of a MATLAB subroutine that takes a Microsoft Excel file as an input, prompts the user for some system data and location of parameters in the Excel sheet, and then cycles through all the data (divided by months) performing the analysis and outputting an Excel file with the analyzed data, including the PVUSA power for both AC and DC, and the performance ratio for both AC and DC as well.[11] The PVUSA analysis performed in this study does not take into account the speed of wind which, in general contributes only 0.4% to the total PVUSA power calculated [12].

System	PR AC (500-1200 W/m²)	PR DC (500 - 1200 W/m²)	PR AC (800 - 1200 W/m²)	PR DC (800 - 1200 W/m²)
CEL	-2.69 %	-2.73 %	-2.42 %	-2.49 %
FAM	-0.68 %	-0.51 %	-0.76 %	-0.57 %
KMS	-1.46 %	-1.44 %	-1.57 %	-1.60 %
MMS	-0.40 %	-0.33 %	-0.38 %	-0.31 %
WFH	-1.08 %	-1.07 %	-1.03 %	-1.02 %

Table 2 Calculated Degradation Using Performance Ratio (%/year)

System	PVUSA AC (500 - 1200 W/m²)	PVUSA DC (500 - 1200 W/m²)	PVUSA AC (800 - 1200 W/m²)	PVUSA DC (800 - 1200 W/m²)
CEL	-2.31 %	-2.34 %	-2.29 %	-2.39 %
FAM	-0.69 %	-0.48 %	-0.62 %	-0.39 %
KMS	-1.93 %	-1.96 %	-2.16 %	-2.18 %
MMS	-0.82 %	-0.75 %	-1.10 %	-1.01 %
WFH	-4.34 %	-4.40 %	-2.31 %	-2.30 %

Table 3 Calculated Degradation Using PVUSA Regression (%/year)

Previous studies performed by Sandia have shown losses on open circuited modules of about 0.5% per year while NREL reports degradation of about 0.7% year [13][14]. Having this in mind leads to various conclusions, which in fact results in obvious calibration problems on some of the systems. Instrument calibration, such as the pyranometer, is of the key for this experiment, which is the primary reason why two of the systems show higher degradation rates than the other calibrated systems. Pyranometer error is the typical cause of the observed high degradation rates. This means constant monitoring and calibration of pyranamoters should be done to ensure readings are accurate. Filtering of data in two different ranges of irradiation showed no difference in the degradation rates calculated. An average difference of 0.02% is observed in the performance ratio analysis while 0.33% is observed in the PVUSA analysis. This is clear evidence that as long as the collected data is clean, the amount of data used per month does not affect the result, although using a larger window of data is better when performing regressions over long periods of time. These two methods use two unique approaches to calculate PV performance. On one hand, the performance ratio analysis uses only the incident irradiation and the output power to determine performance, while the PVUSA analysis considers other factors such as wind speed and ambient temperature along with incident irradiance. The PVUSA analysis should be a better method when used in conjunction with calibrated instruments, because it takes into account more degradation parameters. The analysis of the five PV systems studied led also to a better understanding of seasonal variations, where it was found and confirmed the typical output increase during the colder months, as it would be expected for crystalline technologies. As shown in the collected data for only three systems (figure 5 and 6), the performance ratio analysis clearly shows the variation in performance depending on the different seasons of the year as well as the PVUSA regression analysis.

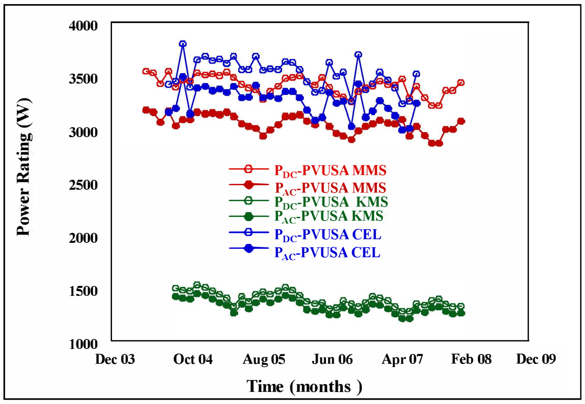

Fig. 5 PVUSA regression for three PV system, plotted vs. time

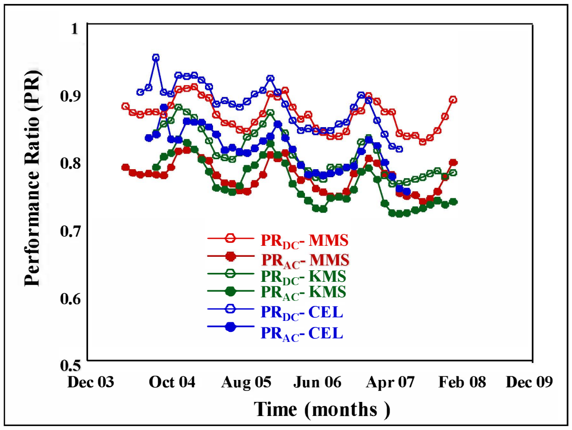

Fig. 6 Performance ratio for three PV system, plotted vs. time

The uncertainty in each variable is propagated through sensitivity coefficients, which are the partial derivatives of the right hand side of equation 1 with respect to each independent variable [15]-[17].

$$P = I_{POA}(a + bI_{POA} + CT_{amb} + dW) \tag{1}$$

Instrumentation error contributes to measurement uncertainty and must be taken into consideration when calculating uncertainties in the measurements taken. These specifications are often constants that can be found on manufacturer specification sheets, each correspond to instrumentation measurement error or uncertainty in each of the equipment that measures irradiance, wind speed, and ambient temperature respectively.

Table 4 below shows the average total uncertainty calculated in the PVUSA Regression analysis performed on the five systems studied in both, 500-1200 W/m^2 and 800-1200 W/m^2 ranges as well as on the AC side and DC side of each system.

System	PVUSA AC (500 - 1200 W/m²)	PVUSA DC (500 - 1200 W/m²)	PVUSA AC (800 - 1200 W/m²)	PVUSA DC (800 - 1200 W/m²)
CEL	±153.51 W	±167.54 W	±139.29 W	±153.48 W
FAM	±200.36 W	±252.61 W	±180.96 W	±229.71 W
KMS	±67.240 W	±68.971 W	±63.510 W	±65.802 W
MMS	±142.19 W	±161.00 W	±139.77 W	±159.96 W
WFH	±146.93 W	±159.96 W	±143.71 W	±158.45 W

Table 3 Average Total Uncertainty in PVUSA Regression Uncertainty

Field Observations and On-Site Measurements

Upon visiting all five sites, a thorough visual inspection was performed, followed by thermal imaging analysis using an IR camera, and I-V measurements using a portable curve tracer (Daystar DS-100). Based on the visual inspections, there were no obvious mechanical or electrical failures, however there were some concerns regarding corrosion of the grounding hardware for all systems (Fig. 7), as well as the mounting hardware and cell cracks. For all systems, there was some very light soiling due to dust and pollen, but this was concentrated at the bottom of the modules, not shading any cells directly. In regards to the thermal imaging, the IR camera showed few signs of hot spots on few of the modules. [18]

In terms of the electrical design, four systems are broken up into two sub-arrays feeding two separate inverters, which were all 2.5 kW nominally rated and one is just one array. *I-V* curves were taken on all sub-arrays. The on-site *I-V* measurements shown in Figure 9 for only one system (MMS) have been translated to ARC using Equations 2-5.

In general the modules showed very little trace of outer degradation. A few modules had some stains in the front glass. But these defects did not result in any significant changes that could separate these from the other modules.

As a point of comparison, the initial ARC-translated power output for the arrays has been included. This initial power output was determined from the archived data set as described in the previous section and was taken as the mean of the ARC-translated power during the first full month of data collection (in both cases, within one year of the installation). In all four cases, the standard deviation fell well within the ±70 W uncertainty given.

$$V_{MP-ARC} = V_{MP-m} + TC_{VMP}(T_{ARC} - T_m) \qquad (2)$$

$$I_{MP-ARC} = I_{MP-m}\left(\frac{G_{ARC}}{G_{POA}}\right) + TC_{IMP}(T_{ARC} - T_m) \qquad (3)$$

$$P_{MP-ARC} = V_{MP-ARC} I_{MP-ARC} \qquad (4)$$

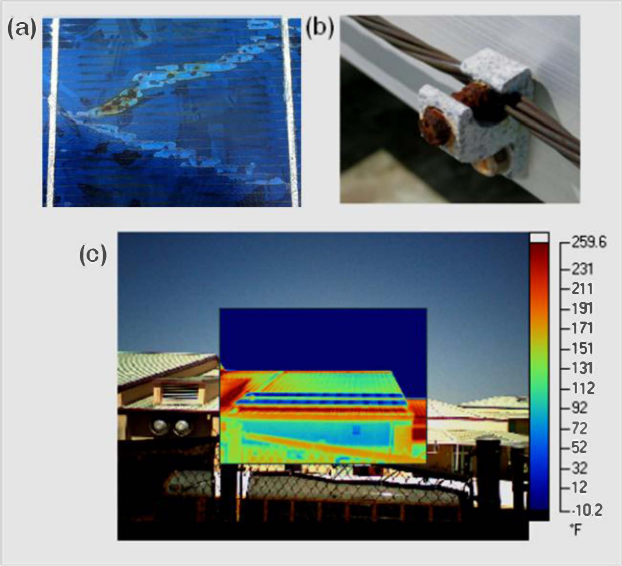

Fig. 7 Pictures of systems: (a) corroded grounding lungs at MMS site; (b) corroded grounding lungs at CEL site; (c) zoomed out IR image of CEL system.

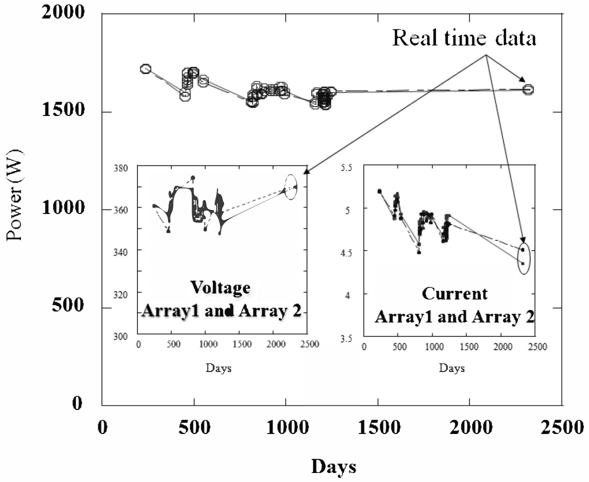

Fig. 8 Real time I-V measurements performed on the MMS system

IV. CONCLUSION

In this study, accurate measurements of data were collected from five individual PV systems installed in the state of Florida, with the purpose of studying their degradation rates. Such data was collected utilizing highly calibrated instruments that measured voltage, current, power, solar irradiation, and temperature every second and averaging it every fifteen minutes. Performing the analysis of five PV systems installed in Florida and monitored by the Florida Solar Energy Center led to a better understanding of the performance and degradation rates experienced by hot and humid field aged PV arrays. With current site visits there is plenty of room to expand this research.

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