REALIZATION OF A SOLAR SIMULATOR FOR PRODUCTION TESTING OF HCPV MODULES

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ABSTRACT: A device capable of quickly, inexpensively, and accurately characterizing module performance in a production setting is necessary for further development of the concentrated photovoltaic (CPV) industry. Without a solar simulator that can reliably and repeatably measure performance characteristics of CPV modules, it will be difficult to market this new technology. SolFocus Inc, in collaboration with the Instituto de Energia Solar at the Universidad Politecnica de Madrid, has developed such a device to support production of its SF1000 CPV module. The system incorporates a number of novel approaches, including a proprietary single-flash measurement system that allows an entire IV curve to be gathered during the extremely short duration pulse of a relatively inexpensive commercial flash strobe and a reference measurement system and uniformity mask tailored to SolFocus CPV modules. The system described in this paper has been in operation at the Noida facility since December 2007 and 100% of modules produced since have been tested. Results of a preliminary correlation study are presented.
Keywords: Concentrators, Test, Solar Simulator

1 INTRODUCTION

SolFocus Inc, a manufacturer of high concentration photovoltaic (HCPV) modules, recently commissioned a production line for its first generation module, the SF1000, in Noida, India. (Fig. 1) This module incorporates 16 concentrating systems, each comprised of primary and secondary mirrors, a non-imaging optical element and a 100 mm2 multi-junction solar cell (Fig. 2), which are referred to as power units. Operating at approximately 500x concentration, the module is rated at 205 W at a direct normal insolation of 850 W/m2 and normal operating temperature.

Figure 1: SolFocus SF1000 HCPV Module

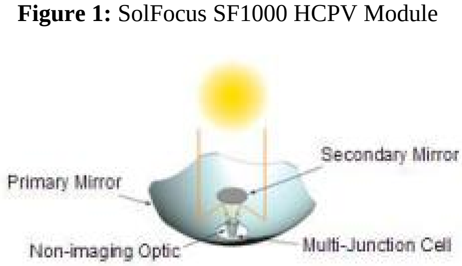

Figure 2: Optics of a single SF1000 power unit

One requirement for the Noida facility was a solar simulator to be used for characterizing the performance of modules, both for peak conversion efficiency and acceptance angle, in a repeatable and reliable manner. As is well known, testing of CPV modules imposes additional requirements for the collimation and spectral qualities of the light. In addition to typical considerations for flat plate solar simulators of light intensity and spatial uniformity, the limited angular acceptance of CPV modules implies that the light be highly collimated with an angular subtense at or near that of the sun. Additionally, because concentrators generally use very high-efficiency III-V multi-junction solar cells whose performance is limited by the lowest performing junction, the requirements for spectrum are more complex. Finally, acceptance angle forms an added important performance metric beyond the IV characteristics traditionally measured by flat-plate simulators, thus CPV simulators require further degrees of freedom to adjust the incident angle of light with respect to the module.

Although systems have been proposed, very few are in use in a production setting and none are available commercially. Therefore, in a collaborative effort with the Instituto de Energía Solar, Universidad Politécnica de Madrid (IES-UPM), SolFocus has developed an industrialized solar simulator capable of characterizing two HCPV modules simultaneously. This system, deployed on Dec. 2007, is capable of supporting a manufacturing scale well in excess of 10MW per year of the SF1000 product, at a 100% sampling rate. It represents one of the first CPV solar simulators operational in a production setting.

To support the production schedule, the development timeframe of this simulator has been very aggressive: approximately 9 months from system definition to deployment. Motivated by the release schedule, a specific design philosophy was adopted which seeks to minimize hardware complexity and technical risk by identifying the most basic requirements and implementing solutions for the specific module type under test. Rather than insist upon ideal illumination, we have found it is sufficient to match the salient characteristics only to the granularity of the device being tested. For instance, the relative performance of triple-junction cells is dependent on the photocurrents produced by the top and middle junctions because under normal operating conditions the bottom junction is saturated. Therefore, rather than attempt to reproduce the solar spectrum exactly, we chose to use our iso-type reference cells to adjust the flash spectrum so that the ratio (between the top and middle photocurrents) matches that observed outdoors for representative conditions. Likewise, spatial uniformity was enforced only at the resolution of single power units using a purpose-built reconfigurable mask.

However this simplifying approach has not precluded innovations where necessary to support production requirements, specifically in the development of a single-flash measurement system that allows an entire IV curve to be gathered during the extremely short duration pulse of a relatively inexpensive commercial flash strobe.

2 SYSTEM DESCRIPTION

This layout of the simulator (Fig. 3) builds off a concept introduced by Dominguez et al. at IES-UPM [1], with a number of improvements aimed at reducing the testing time and costs, as well as improving the accuracy of the test. A low-cost commercial xenon flash strobe is used as a light source. Such light sources have been shown in prior work to be ideally suited for CPV flash testing, because they combine high instantaneous irradiance with very small size. This light source is coupled with an array of spherical reflectors (Fig. 4) to create a beam of collimated light approximately 2.7m x 2.1m in size. The collimation angle of this beam has been experimentally measured to be approximately ±0.34º. The simulator light intensity is adjustable in the range of 500 to 700 W/m2.

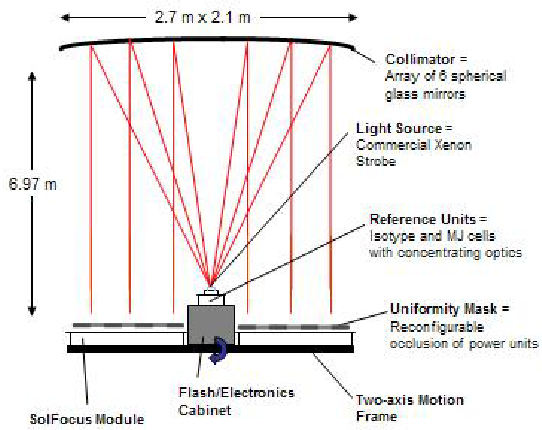

Figure 3: Layout of SolFocus Solar Simulator

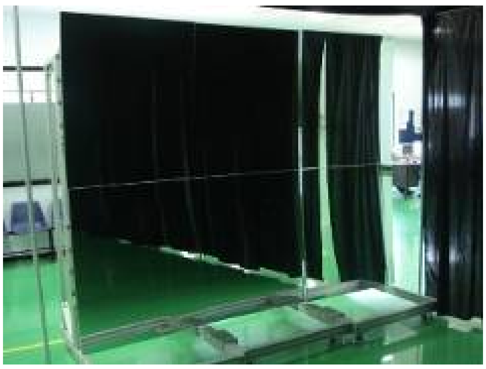

Figure 4: Collimating array of spherical mirrors

Two SolFocus CPV modules are mounted on a dual-axis motion frame on either side of the light source, which is placed at the focus of the collimator. Four reference power units employing identical optics to the module are adjacent to the modules being tested, and are used to measure the irradiance and spectrum of the light. (Fig 5) Proprietary IV-tracing hardware and software have been integrated with a high speed data acquisition system for measuring the IV characteristics of the tested modules as well as transforming the tested IV characteristics into predicted characteristics at normal in-sun operating conditions. To facilitate operation by technician level personnel, the system has been provided with an easy to use GUI (Fig. 7).

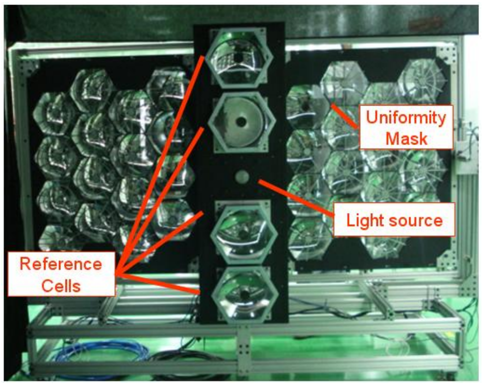

Figure 5: View of exposed area of solar simulator

Figure 6: Loading a module into the motion frame

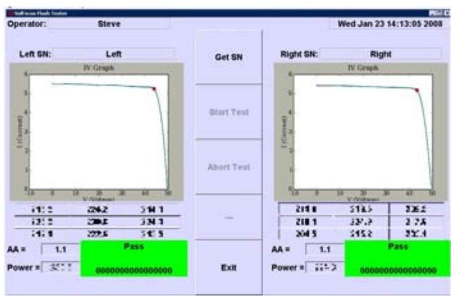

Figure 7: Graphical User Interface

3 REFERENCE POWER UNITS

The simulator employs four reference sensors that allow both irradiance and spectrum to be measured and verified during every test. All of these sensors are multi-junction cells of the same size as those used in the modules to be tested. The first is a standard multi-junction cell and is used for measuring irradiance. The other three are iso-type cells, which are multi-junction cells that have been fabricated such that all but one junction is inactive. The simulator is provided with an iso-type reference for each junction, and therefore can accurately estimate the current being produced by each junction of the modules under test.

All four reference cells are encapsulated within the same concentrating optics used by the SF1000 CPV module, creating a sealed reference power unit, which can be seen in Figure 5, mounted above and below the light source. Such an approach is necessary for CPV solar simulators for two reasons. First, the behavior of multi-junction cells is dependent on concentration. Second, the concentrating optics have a spectral transmission curve that is not neutral. By placing our reference cells under concentrating optics we ensure that they are exposed to light that is identical both in irradiance and spectrum to that which is exposing the cells of the modules under test.

To calibrate the simulator, a set of four reference units are placed in the sun under known conditions of irradiance and spectrum. A reference current is recorded for each unit. This set of four units is then mounted on the simulator, and the flash voltage may be adjusted such that the ratio of the currents generated by the top junction iso-type and the middle junction iso-type approximates ratio of the reference currents for those iso-types within a certain threshold. At the same time, the current from the bottom iso-junction is measured to ensure that it is greater than either the top or the middle junction current.

This procedure eliminates concerns that manufacturing differences in the reference units themselves will affect the calibration. It ensures that the spectrum of the light is sufficiently close to the reference spectrum such that the IV characteristics measured from the modules tested will be predictive of in-sun measurements. Because these reference sensors are permanent part of the device, the irradiance and spectrum may be verified during each test, and spectral drift due aging of the flash bulb or other factors may be detected immediately.

4 IV CURVE MEASUREMENT

Flat-panel single-flash systems rely on pulse forming networks to provide constant irradiance and spectrum while taking an IV curve in a time span on the order of milliseconds. Unfortunately, to achieve the required irradiance level with a constant power pulse of this duration, the bulb must scale to a size that is incompatible with the angular subtense required. Previous demonstration CPV flash systems have used short-pulse light sources with a compact bulb, but were only capable of acquiring one point on the IV curve per flash. [1] [2] This limitation is especially burdensome for CPV because multiple IV curves must be taken at several angles of incidence to estimate angular acceptance. For a SolFocus CPV module, measurement time can be decreased by a factor of 20 or more by using a single-flash method, with a commensurate increase in flash bulb life and therefore test costs.

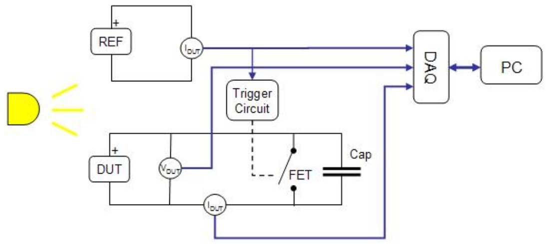

Figure 8: Diagram of IV-Curve measurement system

SolFocus has developed hardware and software that is capable of taking an entire IV curve within 400 microseconds near the peak irradiance of a short-pulse strobe. This system is composed of a triggering circuit, an IV measurement circuit for each module, a high-speed data acquisition system, and a computer. (Fig 8) The triggering circuit receives a signal from the multi-junction reference unit that is proportional to the irradiance of the light. It detects the rise of the flash pulse and sends a trigger signal to each of the two IV measurements circuits. These circuits are equipped with a capacitor bank, a field effect transistor, and a Hall Effect sensor, and are connected to the modules under test. The transistor remains closed, keeping the capacitor shorted, unit this signal is received, at which point the capacitor is charged by the photocurrent of the module under test. The capacitor is sized such that it will reach the V_{OC} of the module under test in the desired amount of time.

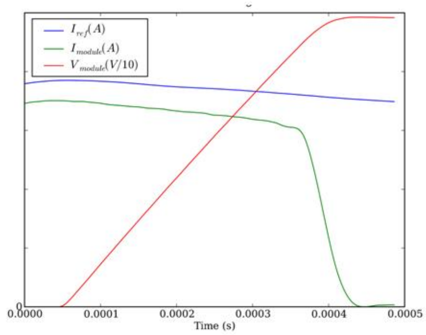

Figure 9: Filtered data in the time domain

Thus the charging of the capacitor by the module causes an increasing load, allowing the IV characteristics to be gathered. Current and voltage of the module during this time are measured with a high-speed oscilloscope and filtered. (Fig 9) Accuracy is maintained during the brief period of the measurement by compensating for the inductance of the module and the time variation of irradiance (Fig. 10). Once the final IV curve is obtained, the max power may be calculated. This power, which represents power at ambient temperature, may be adjusted to standard operating conditions using empirically developed temperature coefficients if desired.

To verify that the curves obtained from solar simulator are predictive of behavior in the sun, we can correct both indoor and outdoor IV-curves to Standard Reporting Conditions by means of a single diode electrical model of the solar cell. As shown in Figure 11, the resulting IV curves are very similar.

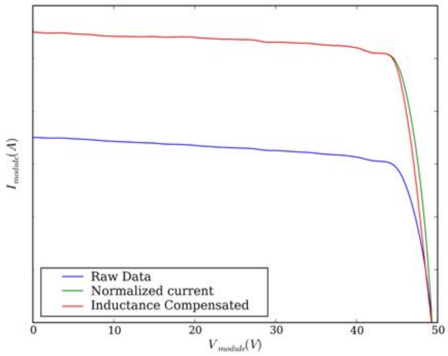

Figure 10: IV Curves before and after irradiance and inductance compensation

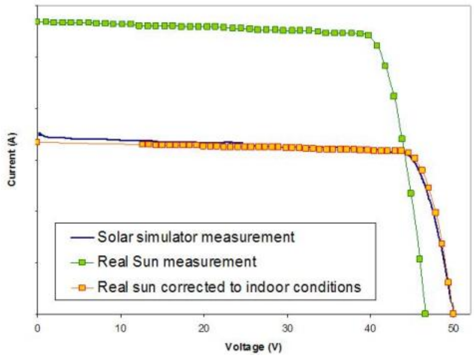

Figure 11: Adjusted IV curve

5 UNIFORMITY MASK.

As mentioned previously, it is important to ensure that the intensity of the light is spatially uniform across the module to be tested. This is primarily because the cells are connected in series, and so if one cell receives less light than another, it will generate less current, and it will limit the entire string. This will affect the IV characteristics, and the peak power of the module being tested and therefore produce results that are not predictive of performance under the uniform light of the sun. However, in the case of CPV solar simulators, we may take advantage of the fact that the module is made up of a discrete number of mini-concentrators. Because all of the light falling on the primary optic of any one of these concentrators will be concentrated onto a single cell, it is not necessary to ensure uniformity across the primary optic. It is only necessary to enforce the uniformity of the light flux entering each mirror.

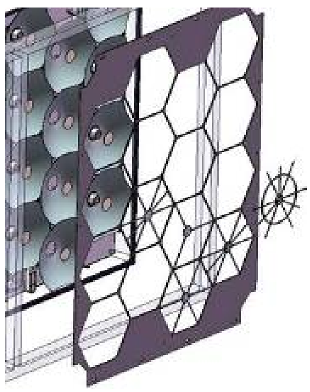

Figure 12: Uniformity mask design

Using this concept, SolFocus has designed a purpose built reconfigurable mask for the SF1000 module. (Fig 12). This is composed of a steel metal grid cut such that when mounted to the motion frame of the solar simulator, follows the boundaries between the hexagonal primary mirrors. Narrow strips of metal can then be mounted to this grid in spoke-like assemblies that are designed to occlude an area that is a pre-determined percentage of the total primary mirror area, and thus reduce the flux incident on the underlying cell by an equal amount. By first measuring the total flux for each hexagonal area and identifying the area that receives the lowest flux, and then fixing the correct spoked assemblies to the remaining 15 power unit positions, we have shown that the flux uniformity drops to below 1% across the module. (Fig 13).

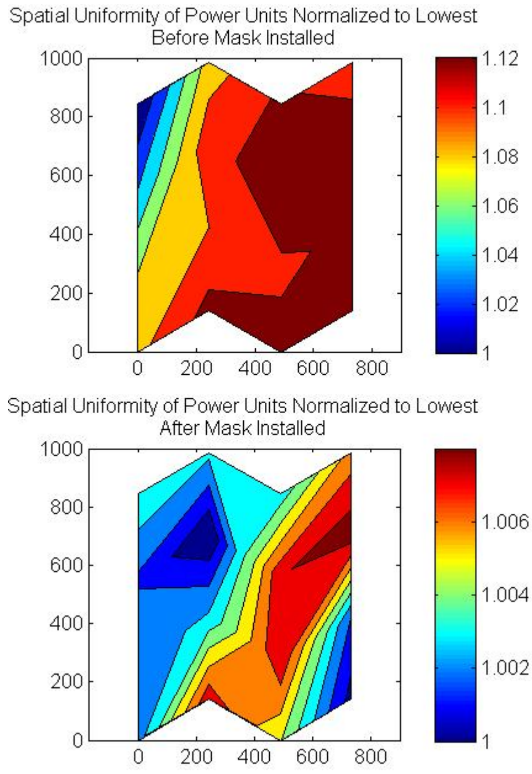

Figure 13: Effect of mask on spatial uniformity across module test area

6 CORRELATION AND RESULTS

The Solar Simulator has already proven very successful as a process control tool. Because every module is tested as soon as it is fabricated, any deviations from baseline performance, either module peak power or acceptance angle, is immediately apparent. Then the route cause of these deviations can be diagnosed and addressed.

Because we have controlled the principle test conditions, we also expect the device be able to predict the performance of the modules tested in the sun at reference spectral conditions. An initial correlation study has been performed on a large population of modules that have been tested both in simulator and in the sun. The maximum power in each case was adjusted to standard operating cell temperature, using an empirically determined coefficient. The standard deviation of these errors is approximately 2.3% of the mean of the power as measured by the simulator. (Fig 14). This number does not well represent the actual prediction accuracy of the simulator, but may be understood as an upper bound. This is because the analysis is limited by a number of factors. First, the modules themselves tend to have a very consistent performance, limiting our ability to understand the correlation. Secondly, although we are attempting to control for temperature, the method used is simplified. Finally, the in-sun tests were taken at different times throughout the day, under light of varying spectral content, and the resulting affect on performance has not been taken into account and therefore contributes to the error in the difference between two data sets.

Further studies will attempt to extend the dataset, measure spectral content during each test, and increase the range of the performance of the modules tested by artificially handicapping them.

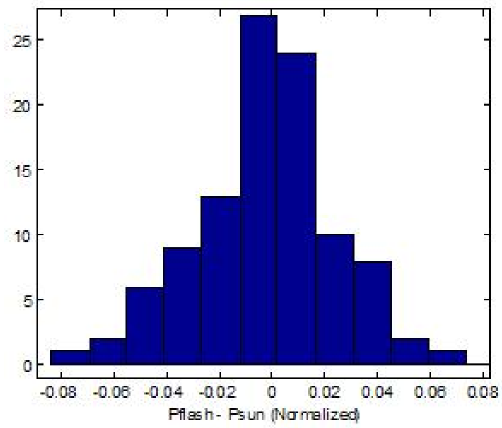

Figure 14: Histogram of the comparison between flash and in-sun results for initial correlation study.

7 CONCLUSIONS

A device capable of quickly, inexpensively, and accurately characterizing module performance in a production setting is necessary for advancing the CPV industry. To reduce the technical risks in developing such a device, SolFocus has used a minimalist approach of simplifying the hardware requirements by tailoring the device to a specific module design. This approach accelerated the development of the simulator, which has become one of the first in the industry to go into operation to support volume manufacturing. Although the simulator produced specifically supports SolFocus HCPV modules, the methodologies reported here can be used to create purpose-built simulators for a wide variety of CPV designs.

8 REFERENCES

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