Calibration Of Collimated Flash Tester For High-Concentration Photovoltaic Panels

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Abstract. Accurate high volume manufacturing final test of high-concentration photovoltaic (HCPV) panels is challenging owing to the spectral sensitivity of multi-junction solar cells, the inherently small angular acceptance, and the elevated temperature during standard operating conditions (CSOC). An industrialized HCPV solar simulator developed in parallel with SolFocus first generation SF-1000S product has been previously discussed. Validation of the regression of simulator performance measurements from test conditions to CSOC was achieved by correlation of solar simulator and on-sun results using more than 100 SF-1000P panels.

The second generation SF-1100S product incorporates a number of design and manufacturing advances including more efficient multi-junction solar cells, more thermally conductive receivers, more transmissive collection optics, and an optimized backpan, as well as a larger collection area. Each of these improvements can affect the accuracy of the regression from simulator test condition to SOC.

To ensure that the SF-1100S product meets industry needs for power accuracy, we discuss the flash test methods and on-sun tests performed to quantify the thermal and optical parameters required for accurate regression to SOC. For cost reasons, cell temperature in standard commercial HCPV panels is not directly instrumented, hence we applied multiple independent measurement methods to ensure accurate estimation. We present best results for measurement of PV cell temperature under operating conditions comparing several methods. We review the correlation between normalized factory test results and standard operating conditions, along with sources of variance in the measurements.

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DESCRIPTION OF FLASH TEST

Flash Test Design

The SolFocus flash test equipment has been described in detail elsewhere [1], [2]. The equipment consists of a flash source, segmented spherical collimating mirror, reference cells used for normalizing measurements and high-speed current measurement to allow I-V curves to be taken within a single flash. The system is shown schematically in **Figure 1**.

Flash Test Method

Because the flash test is performed at less than one sun irradiance and at laboratory temperature, several normalizations are needed to adjust flash test results to be predictive of on-sun performance. The normalization is described by Equations 1 and 2

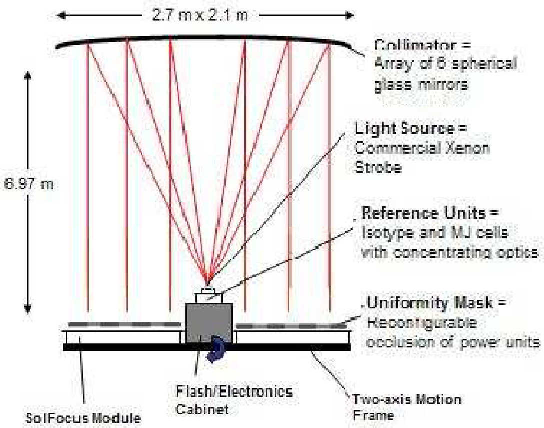

Figure 1. Schematic of collimated flash tester.

$$P_{\text{flash},850} = \max\left(V_{\text{module,flash}} \cdot I_{\text{module,flash}} \cdot \frac{I_{\text{ref,sun},850}}{I_{\text{ref, flash}}}\right) \quad (1)$$

$$P_{\text{flash,CSOC}} = P_{\text{flash},850} \cdot \left[1 - \alpha\left(T_{\text{cell,CSOC}} - T_{\text{cell,flash}}\right)\right] \quad (2)$$

$P_{\text{flash,CSOC}}$ is the predicted on-sun maximum power point performance at CSOC as computed from flash data, using $P_{\text{flash,850}}$, the flash test result normalized to 850 W/m^2, as computed from the measured I-V curve during flash and normalized by the ratio of current in a known reference cell as measured on sun at CSOC to the in-flash measurement ($I_{\text{ref,sun,850}}/I_{\text{ref,flash}}$). α is the known temperature coefficient of power for the panel, and $T_{\text{cell,CSOC}}$ is the known cell temperature at CSOC.

Validation of the regression of simulator performance measurements from test conditions to CSOC was achieved by correlation of solar simulator and on-sun results using more than 100 SF-1000P panels [3].

DESCRIPTION OF ON-SUN TEST

To avoid effects of any pointing errors, all on-sun tests are performed on a calibrated test tracker. In addition, to compensate mounting and individual panel pointing errors, a mapping algorithm scans the tracker in both elevation and azimuth directions and lock tracker offsets at the maximum power point.

Direct solar irradiance is measured by a calibrated Normal Incidence Pyrheliometer (NIP) sensor co-mounted on test tracker. Direct Normal Irradiance (DNI) measured with on board NIP sensor is used to normalized panel power to standardized condition (850 W/m^2).

Finding Power At Maximum Power Point And Associated Operating Temperature

The most straightforward way to measure on-sun performance is to mount the SF-1100P panel on a tracker, and measure I-V curves repetitively. The advantage of this method lies in the use of simple curve tracer instruments, and simultaneous collection of data of interest such as open circuit voltage V_{oc}, short circuit current I_{sc} and the power at maximum power point P_{mpp}. Data can be filtered to remove events such as tracking errors, cloud cover, or other non-standard conditions.

A disadvantage to continuous I-V measurement is caused by excess heating of the cell. During I-V measurement, the panel is at open circuit condition for the majority of the time, leading to a higher operating temperature than at CSOC. A power balance equation (3) using the power ratio that would be dissipated at each cell under CSOC to the power actually dissipated during the test is used to obtain the expected cell operating temperature where $T_{cell,test}$ is the measured

$$T_{\text{cell,CSOC}} \cong 20 + (T_{\text{cell,test}} - T_{\text{ambient}})\frac{(P_{\text{in,CSOC}} - P_{\text{mpp}} \cdot \frac{850}{DNI})}{P_{\text{in,test}}} \quad (3)$$

cell temperature at time of sun test, $P_{\text{in,CSOC}}$ is the expected optical power input to the cells at CSOC based on irradiance and optical transfer function, P_{mpp} is the measured power (an estimate of the electrical power extracted under normal maximum power point tracking), and $P_{\text{in,test}}$ is the input optical power under on-sun test conditions. The power balance ratio term is approximately equal to 1-η where η is the cell electrical conversion efficiency. The power balance ratio is therefore approximately 0.6, or the temperature rise at CSOC is about 40% of the actual measured value.

Various methods have been tried in order to obtain $T_{\text{cell,test}}$. Measurements of backpan temperature, and thermal resistance of the cell-to-backpan element stack suffer from a variety of practical difficulties, such as inaccuracies in thermal resistance measurement, and positional sensitivity of backpan temperature. Alternatively, special cell structures can be fabricated with embedded thermocouples, which give good estimates of cell temperature, but limit testing to specially created panels. Finally, our preferred method is to compute temperature from cell suppliers' published thermal coefficient of V_{oc}, and a measured V_{oc} at room temperature.

Using Programmable Load To Maintain Cell Temperature During On-Sun Test

The large temperature correction of Equation 3 can be improved upon if the cell is maintained at standard operating temperature for the duration of on-sun test. One way to do so is to use maximum power point tracking with a programmable load. By ensuring that the normally expected electrical output $P_{\text{out,test}}$ is achieved, Equation 3 is modified to:

$$T_{\text{cell,CSOC}} \cong 20 + (T_{\text{cell,test}} - T_{\text{ambient}})\frac{(P_{\text{in,CSOC}} - P_{\text{mpp}} \cdot \frac{850}{DNI})}{(P_{\text{in,test}} - P_{\text{out,test}})} \quad (4)$$

The important aspect of Equation 4 compared to Equation 3 is that the power balance ratio term is unity if the on-sun test is performed at CSOC, and will normally be near unity.

The method of holding the panel at steady-state operating conditions using the programmable load with maximum power point tracking requires extra hardware and mppt software, in addition to the I-V tracer that is always needed to collect V_{oc} and I_{sc}. An inherent assumption is that the programmable load will be switched out in favor of I-V tracer on a periodic basis, and that such open-circuit measurements will not detract from the panel performance.

Expected Power At Maximum Power Point Computed From On-Sun Data

Using the measurements for P_{mpp}, DNI and $T_{\text{cell,test}}$, the maximum power point at CSOC can be computed according to Equation 5:

$$P_{\text{sun,CSOC}} = \frac{850}{DNI} P_{\text{mpp}} \left(1 - \alpha(T_{\text{cell,test}} - T_{\text{cell,CSOC}})\right) \quad (5)$$

Control Of Other On-Sun Effects

Tandem multi-junction PV cells used in the SF-1100P panel are spectrally balanced to solar spectrum equivalent to Air Mass 1.5D. Although the solar spectrum was not directly measured during our on-sun test, nevertheless, spectral effect can be minimized by selecting test conditions that are close to AM1.5 based on time of day calculations. Air mass during the test can be estimated using tracker elevation angle using Equation 6. Tests are conducted under clear sky conditions (qualitatively determined) to minimize scattering from small particles and aerosols.

$$X = 1/\sin(h + 244/(165 + 47h^{1.1})) \quad (6)$$

Wind can affect cell temperature significantly due to changes in efficiency of convective cooling. Although we don't measure wind conditions during our on-sun test, care was taken to conduct the on-sun tests within a 0-4 m/s range.

Control Of Other Flash Test Effects

We created a set of reference panels, which are tested on the solar simulator on a daily basis at the manufacturing factory. Simulator parameters (flash intensity, electrical trigger levels) are adjusted to maintain the reference panels within allowable 5 W variation band. If adjustments cannot be performed, production is stopped for lamp change or other repair.

Built-in software also checks the ratio of isotype reference cells for each flash, disqualifying any result with a spectrum which is out-of-range, as judged by ratios of current in each isotype cell.

RESULTS

Correlation Between On-Sun And As-Flashed Performance

For a population of 15 panels, varying in flash test performance predicting P_{mpp} at CSOC between 320 W and 350 W. The standard deviation of the residual error ($P_{sun,CSOC} - P_{flash,CSOC}$) is 5 W, and the mean offset between sun and flash results for the panels is between -4 W and 1 W, depending on the temperature control method employed for the on-sun measurement. The results are summarized in Figure 2 and Table 1.

The mean offset is smaller when the programmable load is used. This is due to the smaller temperature difference between CSOC and as-tested conditions, reducing the uncertainty associated with temperature correction.

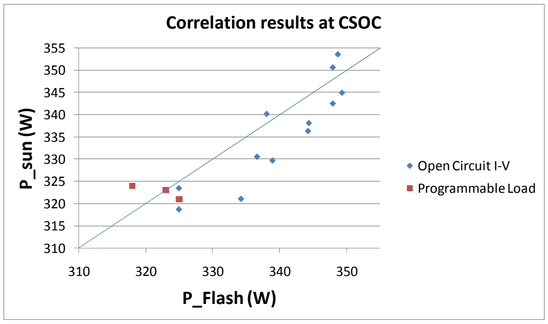

Figure 2. Correlation results between flash and on-sun results, both normalized to CSOC.

Table 1. Sun to Flash correlation summary

On-sun method	Number of panels	Mean shift (sun - flash)	Residual
Open circuit I-V	12	-4 W	5 W
Programmable load	3	1 W	5 W

ANALYSIS

Actual on-sun operating temperature is affected by panel manufacturing variations, time of day (panel attitude), surroundings (effecting thermal dissipation), wind direction and more. Using measured V_{oc}, actual operating temperature variation of the test populations was measured, and is shown in Table 2.

On-sun results are subject to variation in spectrum, both through air mass variation and high-atmosphere scattering. Tests were only performed on high-visibility days and during times of day corresponding to Air Mass 1.3 to 1.7, but careful spectral and scattering measurements would be needed to normalize for these effects.

The methods performed at SolFocus did not include any normalization for wind speed. Measurements were performed under less than 4 m/s wind conditions. A study of changes in convection based on panel angle, wind speed and direction would be needed in order to reduce this effect, or normalization to a standard cell operating temperature determined as representative of CSOC could be developed.

Table 2. On-sun temperature variation

On-Sun Method	Number of Panels	Temperature Variation (σ)
Open circuit I-V	12	4°C
Programmable load	3	1°C

CONCLUSION

Two methods for measurement of panels on-sun under concentrator standard operating conditions (850 W/m^2, 20ºC, AM 1.5, 4 m/s) have been used to verify the calibration of a production level flash tester. Both methods show acceptable results, consistent with ±5% panel rating requirements. The residual discrepancy between flash and on-sun performance can mostly be explained by temperature variations of the on-sun tests, and also by spectral, scattering and wind effects influencing the on-sun test results.

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