Introducing Suns-VR as an enhancement to Suns-V_{OC} for Characterizing Photovoltaic Cells and Modules

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***Abstract*— Suns-V_{OC} has been used extensively to characterize silicon photovoltaics at the cell and system level but does not measure power or current. The addition of a single load resistor, a simple adaptation to Suns-V_{OC}, which we denote as Suns-VR, enables the measurement of the module power and the short circuit current. We demonstrate that by using a single load resistor, we can gather an accurate determination of the efficiency, maximum power, and short circuit current of a solar module by varying the illumination. Combining the Suns-VR and the Suns-V_{OC} allows for a full characterization of solar cells and modules including the parameters of V_{OC}, I_{SC}, FF, P_{MAX}, R_{SERIES}, R_{SHUNT} and ideality factor with applications in both indoor and outdoor testing. This manuscript demonstrates the accuracy of using Suns-VR indoors on a 8-cell module.**

Keywords—Suns-V_{OC}, Suns-VR, efficiency, maximum power point

I. Introduction

The Suns Open Circuit Voltage (Suns-V_{OC}) measurement technique is well established for the characterization of silicon solar cells [1]–[4]. The measurement is conducted by measuring the cell's open circuit voltage at varying light intensities. The result is a pseudo-IV curve reporting characteristics such as pseudo fill factor (pFF). Additional analysis can extract cell parameters such as ideality factor (n), without the effects of series resistance (R_{Series}). The Suns-V_{OC} technique is extensively reported on in the literature, including correction for departures from true steady-state and the generalized analysis [5].

Suns-V_{OC} only captures data using the open-circuit voltage, excluding parameters related to current and power. A complete current-voltage (I-V) sweep is often conducted to complement Suns-V_{OC} to obtain parameters related to current and impacts of R_{Series}. This paper will describe how a simple adaptation to Suns-V_{OC} can be done to extract parameters related to power and efficiency. The technique involves placing a resistor across the device when conducting Suns-V_{OC} measurements, which will be termed Suns-VR (Suns-Voltage-Resistor) to distinguish itself from the standard Suns-V_{OC} technique. The Suns-VR measurement complements, rather than replaces the Suns-V_{OC} technique, and the combination of the two provides a more comprehensive characterization of solar cell loss mechanisms.

A. Module Power Measurement

Conceptually, the output power of a photovoltaic module is measured by placing a variable resistor across the module and measuring corresponding current-voltage points as the resistor is varied under uniform illumination. This concept is commonly performed using an electronic variable resistor [6] but can be performed manually with a variable resistor [7]. Figure 1 shows an example of how the power is calculated using the variable resistor technique, where the numbers are respective resistor values. It may be challenging when manually sweeping to hit the exact maximum power point (M_{PP}) with a constant cell temperature and illumination, due to the resolution of the variable resistor.

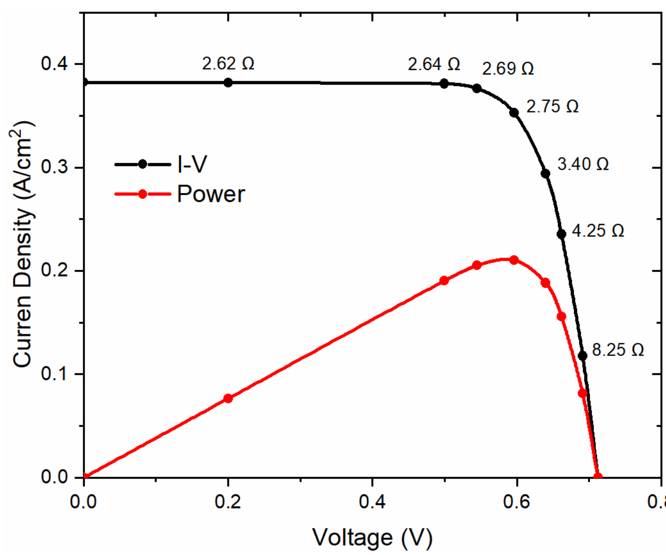

Fig. 1. A simulated manual measured I-V and P-V with a variable resistor. Individual points are labeled with the resistor value used to measure the respective voltage and current.

The Suns-VR procedure for measuring the module output power is shown in figure 2. A resistor is placed across the module's output and measured while varying the light intensity. The load resistance (R_{Load}) can be estimated using the voltage at the maximum power point (V_{MP}) and the current at the maximum power point (I_{MP}) as found in (1).

$$R_{Load} = \frac{V_{MP}}{I_{MP}} \approx \frac{V_{oc}}{I_{sc}} \quad (1)$$

If the resistance value is not optimal, then the efficiency reported at the curve maximum is still the maximum power point, just at a light intensity different from one sun. A more

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optimal resistor value will provide a better approximation of diode parameters under one-sun illumination.

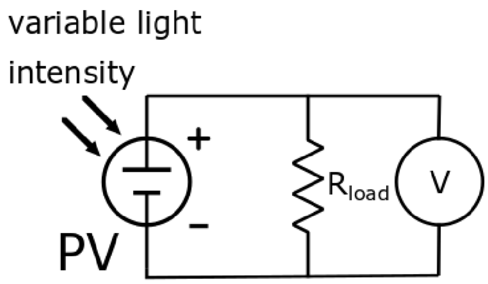

Fig. 2. Circuit schematic used for retrofitting Suns-V_{OC} for Suns-VR measurements.

Using Suns-VR, the power output is calculated using (2), where the load resistance is a stable known value. If drift within the load resistor is suspected, e.g. due to heating, the current is measured separately. Suns is used as a convenience unit to describe illumination as fractions of 1 kW/m^2.

$$Power = \frac{{V_{load}}^2}{Suns \times R_{load}} \tag{2}$$

The data from the Suns-VR can be plotted in a variety of ways. By plotting the data normalized to irradiance, the apex of the curve is equivalent to the M_{PP}. Figure 3 displays the modeled normalized power output using different load resistances. When the load resistor is inadequately sized, the M_{PP} is reported at a light intensity different to one sun. However, efficiency changes slowly with light intensity so the value of M_{PP} at the apex is close to the one-sun value even for resistance values with a large departure from the ideal (15 Ω in this case).

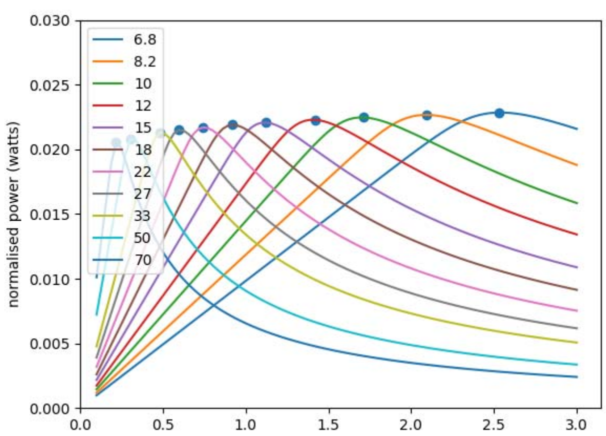

Fig. 3. Modeled normalized power of a solar module using Suns-VR methodology with varying resistor values as denoted in the legend.

B. Implementation of Suns-VR for Modules

When conducting Suns-VR measurements. the light must be varied from 0 to 3 suns, depending on the sizing of the load resistor. The light variation can either be done with an electronic flash, neutral density filters, or simply angling the module to the light source such as the sun. Uniformity across the module is key to mitigating mismatch error. An indoor environment must be clear of objects that may cause reflections and scattered light. The setup must be optimized to ensure appropriate light intensity distributed at a uniformity appropriate for the module size.

Implementing Suns-VR in an outdoor environment is possible, but more variables are introduced as compared to an indoor measurement. One must ensure uniform light is available, by measuring during clear sky conditions. If the module is being tilted to manually vary the light, reflections must be considered [8], [9]. The module could be measured throughout the course of a day to achieve natural light variations, but a large power resistor must be used to mitigate the effects of drift due to temperature extremes from power dissipation. The module operating temperature is arguably the most important variable impacting outdoor measurements. Module voltages proportionately decrease with increased temperatures [10]. Measurements are likely to be recorded at different temperatures, therefore requiring temperature normalization.

The main requirement for Suns-VR is monitoring the light intensity of the illumination source, with a sensor that has a similar response as the device under test. A monitor cell with a similar angular response as the module under test factors out effects such as reflection from the glass. Using the same architecture as the module eliminates mismatch effects such spectral response [11].

In this work, an 8-cell monocrystalline silicon module was fabricated for indoor measurements. The 8-cell module is comprised of a single cell diced into eight equal pieces and soldered together in a series connection. Therefore, the power of the module remains unchanged, but the higher voltages allow for usage of more common resistor values. A monocrystalline silicon cell with similar encapsulation of glass-EVA-backsheet, was used as the sensor cell.

II. Results

Measurements were conducted at approximately 25 ^{o}C using a Xenon flash as the illumination source. Using a horizontal orientation, the flash was setup at a height of 1.5 m and a lateral distance of 3 m from the module surface. A 45x60 cm rectangular flash diffuser was used to disperse light equally across the surface area of the module. Figure 4 shows the spatial uniformity of light across the 1 x 1.5 m surface in units of normalized suns.

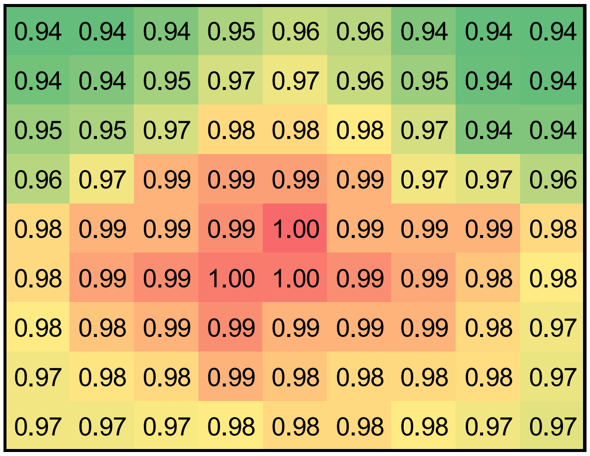

Fig. 4. Spatial uniformity of the Xenon flash located 3 m from the module surface in the units of normalized suns.

The uniformity in figure 4 has a deviation of roughly 5% from the center to the outside corners. It results in an error of similar magnitude when measuring modules greater than 1 m in length due to cell mismatch. Because the module in this experiment is less than 0.2 m in length, the flash mismatch is less than 2%.

Using the module's ratings of 1.19 A for I_{MP} and 3.86 V for V_{MP}, a resistor of roughly 3.2 Ω was needed to induce operation at M_{PP} at approximately one sun. Resistor values of 2.2 Ω, 3.3 Ω, 3.9 Ω, 4.7 Ω, 5.6 Ω, and 6.8 Ω were used to quantify the resulting differences.

The normalized powers are plotted below in figure 5. The apex of each curve is the maximum power (P_{MAX}) for each resistor value. The slope of the curve leading up to the M_{PP} provides the I_{SC} as found in equation (3). It is important to only use the linear portion of the slope before reaching the M_{PP}.

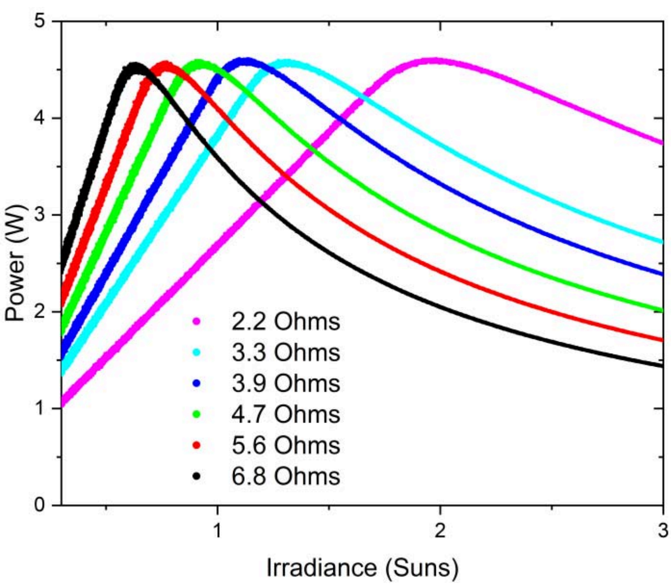

Fig. 5. Power as a function of light intensity using Suns-VR with different resistor values on a crystalline silicon module.

$$I_{SC} = \frac{\Delta Voltage}{\Delta Suns \times R_{load}} \quad (3)$$

Table 1 provides the P_{MAX} and the sun intensity at which the M_{PP} was attained, the I_{SC} as calculated from (3), the efficiency as calculated by Suns-VR, and the corresponding values when using a conventional flash tester to measure the I-V curve. As seen in the results, increased resistor sizes decrease the level of illumination needed to measure the M_{PP}. The I_{SC} has minor discrepancies with the flash testing results, which is likely due to spectral differences from the flash.

TABLE I. MAXIMUM POWER & CORRESPONDING ILLUMATION VALUES USING SUNS-VR ON A SILICON MODULE

Resistor Value (Ω)	P_{MAX} (W)	Suns at P_{MAX}	I_{SC} (A)	n
2.2	4.61	1.98	1.11	20.49%
3.3	4.59	1.27	1.09	20.42%
3.9	4.61	1.10	1.09	20.49%
4.7	4.59	0.90	1.08	20.40%
5.6	4.58	0.77	1.08	20.34%
6.8	4.56	0.63	1.08	20.27%
I-V Flash	4.60	1	1.19	20.42%

III. Discussion

By using different size load resistors, the M_{PP} reported were all within a deviation of roughly 1.5%. This deviation falls within the resistor's tolerance of ± 5%. This suggests that the results are still valid if the resistor is not sized exact to the optimal size.

Varying the load resistor size can purposely done to induce different injection levels without manipulating the illumination source. By oversizing the load resistor, the M_{PP} is found at a lower injection level, and vice versa. Intentionally manipulating the injection level can induce different recombination effects. Auger recombination typically manifest at high injection levels [12]. Analyzing Suns-VR at low injection level provides more specific insight to how Shockley-Read-Hall (SRH) recombination effects are potentially impacting the module [13].

Further optimization of the diffusers to improve uniformity enables the testing modules of larger surface areas. This work was conducted to provide practicality at a smaller scale but can easily be scaled up with a proper illumination source. Further work can be done to scale the approach to outdoor usage, enabling a new technique for measuring fielded systems.

IV. Conclusion

Suns-VR is a simple method to enhance the commonly used Suns-V_{OC} characterization technique. Any Suns-V_{OC} assessment can be easily retrofitted to perform Suns-VR with the addition of a properly sized load resistor.

Suns-VR provides analysis of the M_{PP}, efficiency, and I_{SC} at different illumination levels. Suns-VR measurements agreed with flash testing I-V measurements, with less than 1% difference for P_{MAX}, 1% difference for efficiency, and 8% difference for I_{SC}.

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