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Linearity Testing of Photovoltaic Cells

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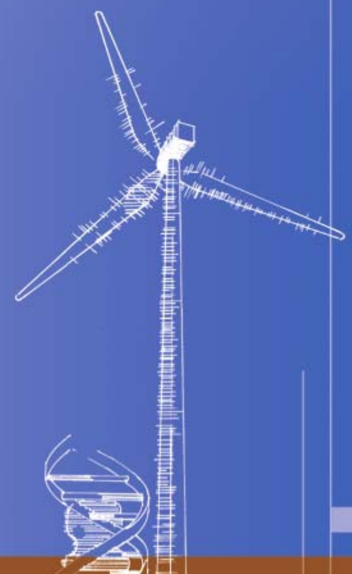

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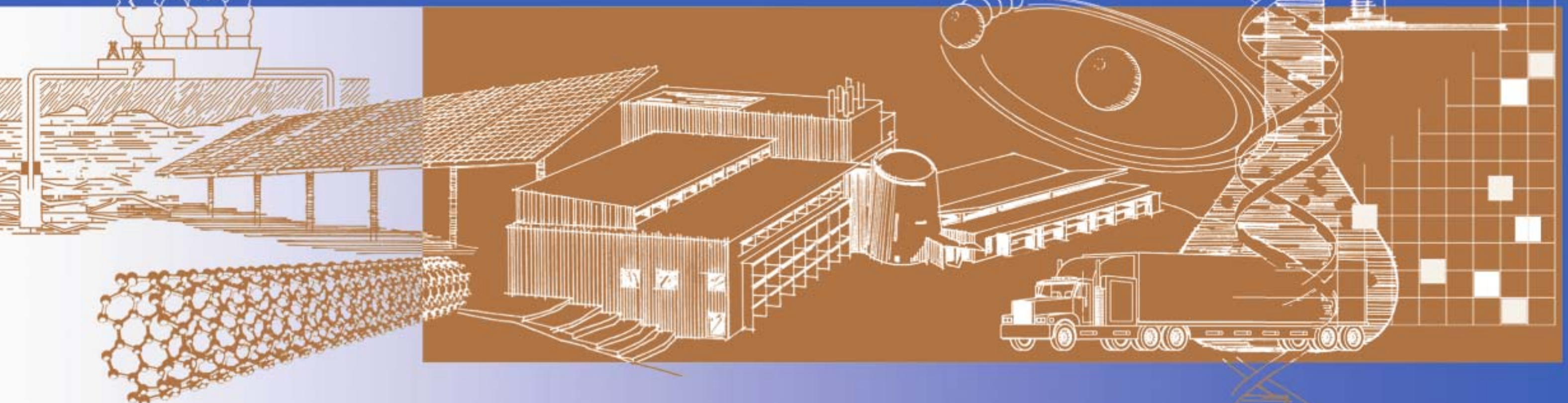

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LINEARITY TESTING OF PHOTOVOLTAIC CELLS

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ABSTRACT

Photovoltaic devices are rated in terms of their peak power with respect to a specific spectrum, total irradiance, and temperature. To rate photovoltaic devices, a reference detector is required whose response is linear with total irradiance. This paper describes a procedure to determine the linearity of the short-circuit current (I_{sc}) *versus* the total irradiance (E_{tot}) by illuminating a reference cell with two lamps. A device is linear if the current measured with both lamps illuminating the cell is the same as the sum of the currents with each lamp illuminating the cell. The two-lamp method is insensitive to the light spectra or spatial nonuniformity changing with irradiance. The two-lamp method is rapid, easy to implement, and does not require operator intervention to change the irradiances. The presence of room light only limits the lowest irradiance that can be evaluated. Unlike other methods, the two-lamp method does not allow the current to be corrected for nonlinear effects.

INTRODUCTION

International standards require that the short-circuit current or response of the reference device is linear with total irradiance [1,3]. Accredited calibration laboratories can not assume that their reference device is linear unless another accredited laboratory has performed the measurement [4]. The PV performance laboratory is ISO 17025 accredited for primary reference cell, secondary reference cell and secondary module calibrations [5]. Limited labor resources necessitated the development of a technique to determine linearity without taking significant labor or skill.

Traditional methods listed in the standards involve measuring I_{sc} *vs*. E_{tot} as E_{tot} is varied, or measuring the differential spectral responsivity *vs.* bias light. Measuring I_{sc} *vs*. E_{tot} assumes that the temperature, spatial nonuniformity, and relative differential spectral irradiance are invariant with E_{tot}. Calculating I_{sc} from spectral responsivity *vs*. bias light gives the correct value for linearity under a given reference spectral irradiance in the absence of errors. All methods assume that the temperature does not change with irradiance and that the light-source spectrum resembles the solar spectrum. The two-lamp method assumes that the lamp intensities when individually irradiating the sample are the same as when both lamps irradiate the sample.

The two-lamp method is insensitive to the spectrum of the light or spatial nonuniformity changing as the irradiance is varied. It does assume that the temperature does not change with irradiance and that the light-source spectrum resembles the solar spectrum. This requirement is only because nonlinear mechanisms in the photo-current are often wavelength dependent because surface recombination, band-gap or diffusion length changing with injection level result in wavelength dependent changes in the photo-current [6]. An extreme example would be a laser showing a device to be linear or very nonlinear with irradiance depending on the wavelength. The two-lamp method assumes that the lamp intensities when individually illuminating the sample are the same as when both lamps illuminate the sample. The presence of room light only limits the lowest irradiance that can be evaluated. Unlike other methods, the two-lamp method does not allow the current to be corrected for nonlinear effects. The

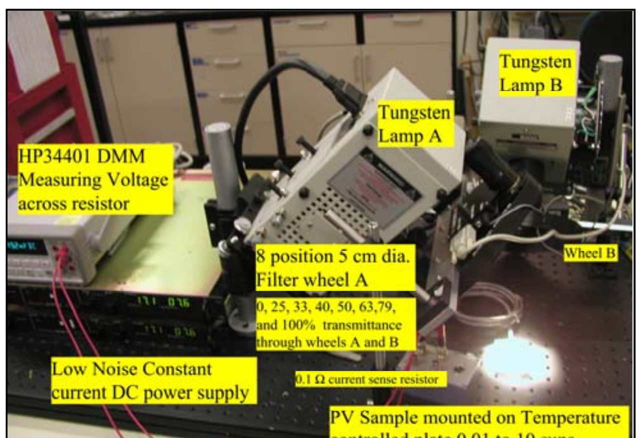

Figure 1. Experimental apparatus to verify linearity.

most appealing aspect of the two-lamp method when compared with other methods for a high-volume calibration laboratory, when implemented as described below, is that it is fast and does not require operator intervention to change the irradiances.

APPARATUS

The experimental apparatus for the two-lamp method is shown in Fig. 1. The light box enclosing the system was removed for the photograph and is not essential. The minimum irradiance that the linearity measurement can be made is determined by the background irradiance and noise in the current measurement. The 8-position filter wheel has a 5-cm clear aperture and is controlled with RS-232 commands. The transmittances of the metallic 5-cm-diameter neutral-density filters were standard values of 25, 33, 40, 50, 63, and 79%. The first two of eight positions are transparent and opaque. The filter wheel is placed so that no light from the lamp leaks out the sides. Any light leaking out the sides that the cell collects is an error if different filter positions leak different amounts of light. The sample is mounted on a temperature controlled plate.

The software automatically adjusts the power supply current to the lamps until the maximum desired light level is reached. For 1-sun reference cells this value is typically 1.4 suns. The program waits for the lamps to stabilize and then rotates the wheels through the 64 combinations of positions. The data is saved and plotted in the groups standard format.

If the intensity of the lamp or cell temperature drifts appreciably during the measurement it may be desirable to install high speed shutters between each lamp and filter wheel with the same constraints of no light leakage. With separate shutters the time for the 3 required measurements for each irradiance can be reduced to the shutter speed and time to read meter because the filter wheels do not need to rotate. Without the shutter the time between the 3 measurements approaches the time for the entire measurement. This also would free up another position on the filter wheel giving 7 filters and one transparent position. The major issue would be the additional expense of hardware and software to control the shutters with the computer.

THEORY

The two lamp method for linearity determination is based upon the linearity of the photo-current with the photon flux. It is assumed that the short-circuit current, I_{sc} equals the photo-current. If a PV device is linear then the superposition principle must be valid: The photo-current from a cell illuminated by two light sources must equal the sum of the photo-currents from the individual light sources or;

$$[I_A - I_{room}] + [I_B - I_{room}] = [I_{AB} - I_{room}] \quad (1)$$

where:
I_{AB} is the short-circuit current with lamps A and B illuminating the cell,
I_A or I_B is the short-circuit current with one lamp on the cell and the light from the other lamp blocked,
I_{room} is the short-circuit current when the light from both lamps are blocked.

Expressing equation 1 as a percentage deviation from linearity, D_{lin} yields;

$$D_{lin} = 100 \bullet [(I_{AB}-I_{room}) / (I_A + I_B -2 \bullet I_{room}) - 1] , \quad (2)$$

A graph of D_{lin} versus the irradiance, E_{tot} will show the percent deviation from linearity with irradiance. The irradiance, E_{tot} can conveniently be expressed as the number of suns,

$$E_{tot} = I_{AB} / I_{sc}(\text{1-sun}) \quad (3)$$

where:
I_{sc}(1-sun) is the estimated short-circuit current under standard reference conditions.

The error in E_{tot} because I_{AB} is nonlinear with irradiance is unimportant because the pass / fail criteria as described below is based upon the maximum percentage deviation from nonlinearity and not the irradiance. For pass / fail criteria based upon the standard deviation of the slope of E_{lin} *versus* E_{tot} the standard deviation will be affected. However, the curve would not be made more linear by an error in E_{tot}.

RESULTS

Both ASTM and IEC standards determine if a sample is nonlinear by the standard deviation of the slope expressed as a percentage [7,8]. A cell is deemed nonlinear if the standard deviation in the slope of a linear fit to I_{sc} *vs.* E_{tot} is greater than 2%.

Figure 2 compares PTB calibration results with the two lamp method [9,10]. Nonlinear effects are not readily apparent when I_{sc} versus the total irradiance is plotted. A better way to look at the data is shown in Fig. 3, where the data are normalized and expressed as a percentage deviation from linearity at 1-sun, D_{lin}. This form is also how PTB presents their linearity measurements in their reference-cell calibration certificates. The two-lamp method is similar, but shows more "scatter" because the nonlinearity over a range of irradiances is expressed at any given total irradiance. Another source of scatter in the two lamp method as implemented in this paper is the 0.3% maximum drift in the 2 lamps irradiance during the measurement period.

An exact numerical calculation was performed to assess the differences between the two-lamp method and the more traditional approach of measuring I_{sc} *versus* E_{tot}. A quadratic function designed to give a 1-sun I_{sc} of 100 mA and linear fit to the function over a 0.3 to 1.4 sun irradiance range giving a standard deviation / slope of 2% yields;

$$I_{sc} = (75.28 + 23.74 \bullet E_{tot}) \bullet E_{tot} \quad (4)$$

Figure 4 summarizes these results. The most notable feature of the exact calculation is that a standard deviation of 2% does not ensure that the maximum deviation from linearity is less than 2%, as suggested in ASTM standard E1143 section 8.2 or in IEC standard 60904-10. Differences between the two-lamp method and traditional measurements are a function of the nonlinearity. Because of these differences, the two-lamp method is limited to determining the nonlinearity over a relatively narrow irradiance range such as 0.3 to 1.4 suns.

An example of a device showing nonlinear behavior because of internal series resistance is given in Fig. 5. This graph was produced by Labview software as part of the linearity test bed's output. Figure 6 shows how series resistance can impact the linearity. At light levels above one sun values near I_{sc} are reduced because of resistance losses. Similar behavior can also occur if the cell voltage is too large and the parameter being measured is not the photo-current but closer to the open-circuit voltage.

The quality of the two-lamp method data is determined by the variation in the lamp output during the measurement and the range of temperatures during the measurement since the procedure assumes that the temperature does not change. Typically the lamp drifts in intensity less than 0.4% resulting in a 0.4% or large uncertainty in the nonlinearity. This value can be reduced by reducing the time between measuring I_A , I_B , and I_{AB} as close together in time as possible. The temperature change during the measurement is an issue with all methods involving continuous light because the temperature gradient between the cell and sensor and between the sensor and the temperature controlled plate varies as a function of light level. For well behaved cells this change is typically less than 2 °C. For the cell shown in Fig. 5 the temperature varied by 6 °C during the measurement.

SUMMARY

In summary a method has been presented to determine if the short-circuit current is linear with light level over the range of interest for flat-plate photovoltaic technologies. The method is rapid, does not require operator intervention and produces a quantitative graph of percentage deviation form linearity as a function of light level. It is anticipated that this method will be incorporated into consensus standards. The standard deviation of the slope of I_{sc} *versus* total irradiance is poor indicator of nonlinearity and should not be used. It is recommended that nonlinearity be expressed as a percentage deviation form linearity versus total irradiance.

ACKNOWLEDGEMENTS

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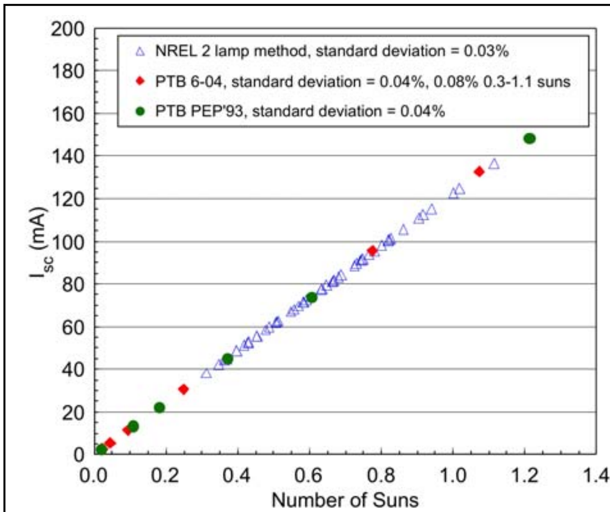

Figure 2. Linearity measurement of WPVS primary reference cell 930216-1 from two calibrations at PTB 10 years apart compared with the two-lamp method.

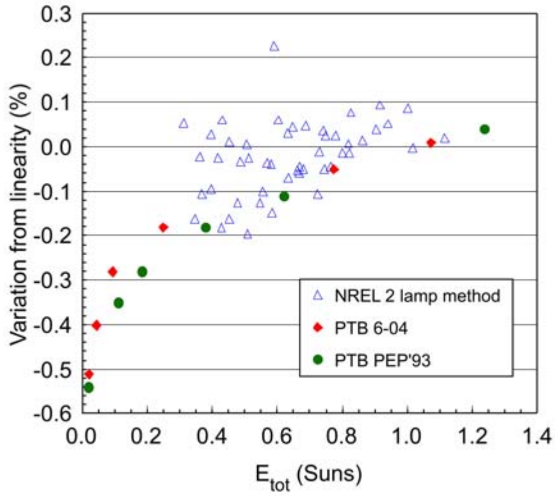

Figure 3. Linearity measurement of WPVS primary reference cell 930216-1 expressed as a percentage deviation from linearity.

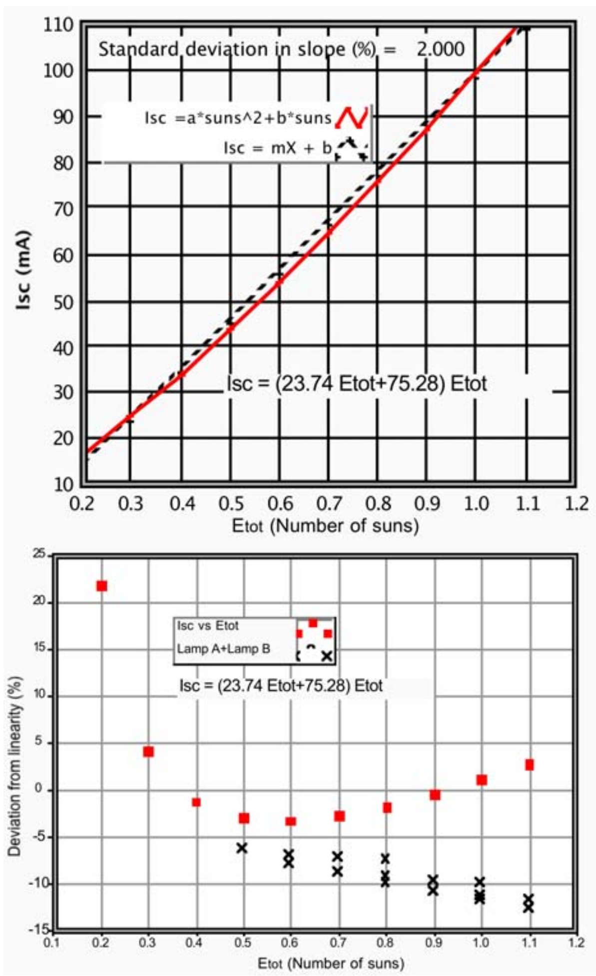

Figure 4. Exact calculation of a simulated device that fails the ASTM and IEC linearity requirements, showing that the deviation from nonlinearity can be more than 2% even though the standard deviation is 2%.

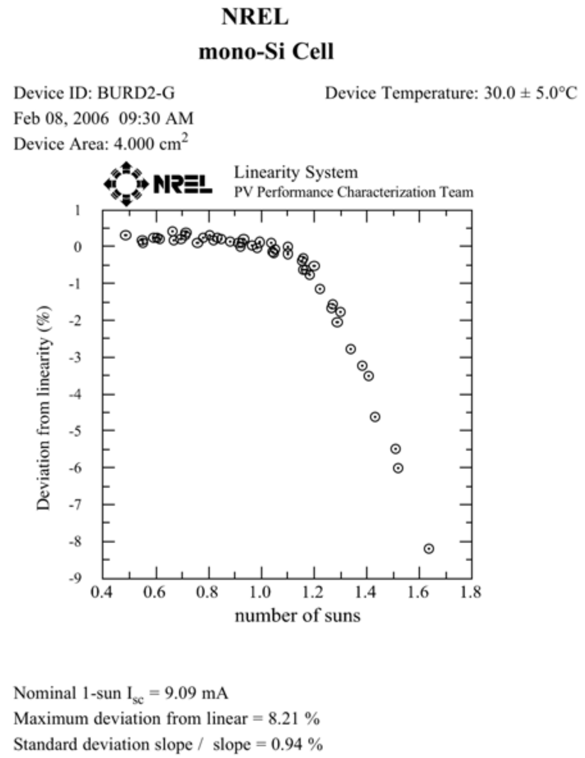

Figure 5. Standard plot from Two-Lamp Linearity Measurement system showing nonlinear behavior because of an internal series resistance in a reference cell at light levels above 1-sun.

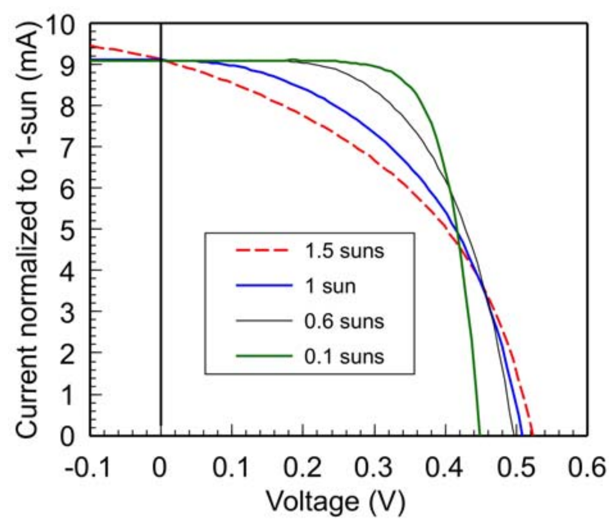

Figure 6. Normalized Current *vs.* voltage for nonlinear cell in Fig. 5 showing that at light levels above 1-sun the photo-current is not I_{sc}.