AN INEXPENSIVE SPECTRAL SENSOR FOR MMPT IN PARTIAL SHADE

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ABSTRACT: Metrics such as the Useful Fraction (UF), the Weighted Useful Fraction (WUF) and the Average Photon Energy (APE), have been proposed and successfully used to demonstrate the relationship between the spectrum of the incident radiation and solar cell performance. In this work we propose the use of a new inexpensive optical sensing technology to accurately determine the spectrum of incident light and hence the UF, WUF, APE and Photon Absorption rate in real time. These sensors could be integrated within a photovoltaic system to gather data for a maximum power point tracking (MPPT) system that can deal with challenging partial shading conditions.

Keywords: Amorphous Silicon, c-Si, Calibration, Devices, Solar Radiation, Shading,

1 INTRODUCTION

There is an output voltage at which the maximum power can be extracted from a photovoltaic (PV) system. Unfortunately, this maximum power point depends upon environmental factors, particularly irradiance and operating temperature, that are time dependent. Consequently, to ensure efficient operation of the system maximum power point tracking has to be employed. If all the individual PV cells in a module are operating under the same conditions, the necessary tracking of the resulting unique maximum power point can be achieved using one of a number of existing maximum power point tracking (MPPT) techniques [1]. However, this is not the case when some of the cells in a module are shaded, either by an object or by a passing cloud. Under these conditions several local maxima in output power can arise at different output voltages. Any MPPT strategy that fails to find the global maximum power point can lead to a loss of power of 70% at some instances and between 1% and 2% over a whole day [2].

A possible approach to avoiding these losses is based upon a comprehensive study of the characteristics of partial shaded PV systems [3]. This study showed that the maxima in output power always occur at a voltage that is approximately an integer multiple of 80% of the open circuit voltage of a module. This means that the global maximum can be found by using an existing MPPT technique to determine the maximum power available at voltages close to these known voltages [3]. Since the conditions that determine the optimum output voltage can change rapidly, the search for a new global maximum has to be undertaken regularly, possibly every 25 seconds, or when a site supervisor initiates a search [3]. The need for these regular searches or intervention by a supervisor could be avoided using sensors to determine the pattern of shading. Furthermore, since the location of the global maximum is related to the pattern of shading these sensors could provide the information needed to determine the probable location of the global maximum when conditions have changed.

Inexpensive sensors placed close to modules could determine the irradiation falling on each module. However, the performance of PV cells depends upon both the intensity and the spectrum of irradiation. Sensors are therefore required that determine a parameter that is related to the spectrum of the irradiation. One parameter that could be calculated by the sensor system is the Useful Fraction (UF) [4]. One major assumption in the definition of UF is that the spectral response (SR) of the PV cells is 100% for wavelengths that can be absorbed by the PV cell. However, not all of the incident energy that is within the cell's spectral range will be converted to useful energy. To compensate for this the Weighted Useful Fraction (WUF) was introduced [5]. For a PV cell design with a spectral response SR(λ), where λ represents the wavelength, irradiated by an illuminant with a spectrum E(λ) the weighted useful fraction (WUF) is defined as

$$WUF = \frac{\int_{cell-\min}^{cell-\max} E(\lambda) SR(\lambda)\, d\lambda}{\int_{observed\_radiation-\min}^{observed\_radiation-\max} E(\lambda) d\lambda} \quad (1)$$

Since UF is calculated assuming SR(λ) = 1 in the range of the cell absorption in Equation 1, UF is always bigger than WUF. Alternatively, Jardine and co-workers have shown a strong correlation between the average photon energy (APE) the short circuit current in single junction devices [6].

Previously, a simple multispectral imaging system that can obtain accurate estimates of the spectra of skylight from a combination of a small set of optimized Gaussian sensors and the Imai-Berns spectral estimation method has been developed [7,8]. In a similar work, the Imai-Berns method was used to estimate the spectrum of skylight based upon the responses of a 3-sensor commercial scientific CCD camera [9]. Recently, the ability to integrate Fabry-Perot filters with a full width at half maximum (FWHM) of between 10 nm and 25 nm on top of the pixels of an otherwise standard CMOS imager has been demonstrated [10]. This technology could be used to create inexpensive sensors that could be integrated as part of a MPPT system that is robust to shading of some modules in a system. The aim of the work reported in this paper is to investigate the number of sensors that would be required and the accuracy with which key parameters can be estimated.

2 DESCRIPTION OF THE EXPERIMENTAL DATA

To obtain statistical significant results, a set of 2600 spectral daylight irradiance measurements taken in Granada (Spain, 37.18ºN 3.60ºW) over two years has been used. This data was acquired with a cosine receptor attached to the spectro-radiometer and it represents the irradiance from the whole sky dome [11]. These data cover the wavelength range from 300nm to 1100nm in 5nm steps, and hence allow us to estimate the total number of photons that could be absorbed by any material that absorbed these wavelengths, including both a-Si and c-Si. However, the work that is reported assumes an absorption spectrum that represents an a-Si PV cell.

An investigation of this data showed that there were strong correlations between the UF, the WUF and the APE metrics. In contrast, the results in Figure 1 show that there is no correlation between the UF and the correlated color temperature (CCT) which can be calculated from spectral data). This suggests that CCT will not be a useful measure of the output of a PV cells irradiated with the same light as the sensor.

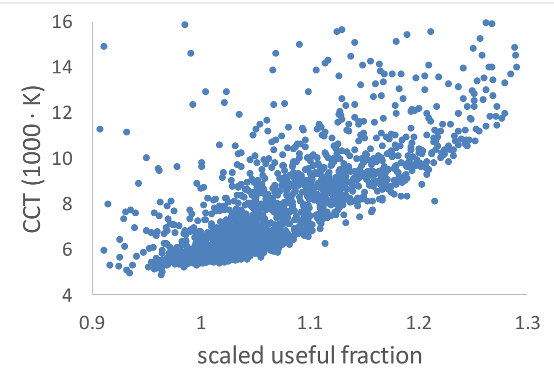

Figure 1. Color temperature in K as a function of scaled UF for our dataset.

Spectral estimation methods, like the Imai-Berns method, provide unrealistically good results when the training set of spectra (required for these methods to be used) and the test set are the same. In our case, when we use the Imai-Berns method for estimating spectra from sensors responses, and then calculate the UF, WUF or APE from those estimated spectra, we use a subset of 100 spectra extracted from the whole dataset as a training set, by maximizing a distance metric among the selected spectra. The accuracy of the spectral estimation method was then determined using a separate representative set of spectra. The selection of this subset for training was done following the method described in [9], which proved to be very effective at obtaining a training set which is representative of the results that would be obtained from the whole data set [9].

3 DESCRIPTION OF THE SYSTEM

Although the Imai-Berns method has been required previously to estimate CCT and other metrics that require spectral or colorimetric information, it may be possible to estimate UF, WUF and APE by simply combining the responses of a set of Gaussian sensors with spectral responses that peak at wavelengths that are evenly distributed across the wavelength range of interest, with a spectral separation among peaks not much higher than their spectral width. For example, Figure 2 shows the results obtained when using a weighted sum of the spectral responses of Gaussian sensors whose spectral responses are separated by 20nm and that are 20nm wide, to build an approximation of the spectral sensitivity curve of a typical a-Si cell [12]. For the case of the UF, the spectral profile to simulate is constant and equal to one, as we show in Figure 3, and can also be approximated by combining the responses of a set of sharp, equally spaced Gaussian sensors. Hence, we only need to adequately sum these sensors responses in order to obtain the total number of photons absorbed by the PV cell (numerator in Equation 1) for WUF, or the total number of photons available at the spectral range of interest for UF. We assume that the total irradiance impinging on the cell (denominator in Equation 1) can be measured by using a pyranometer or a similar device.

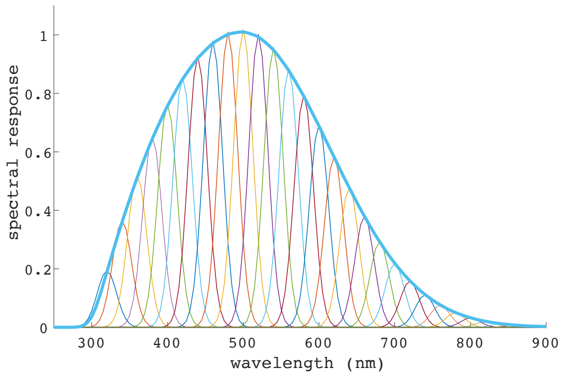

Figure 2. The solid blue curve is the sum of the weighted responses of 20-nm width Gaussian sensors, the peaks of which are separated 20nm.

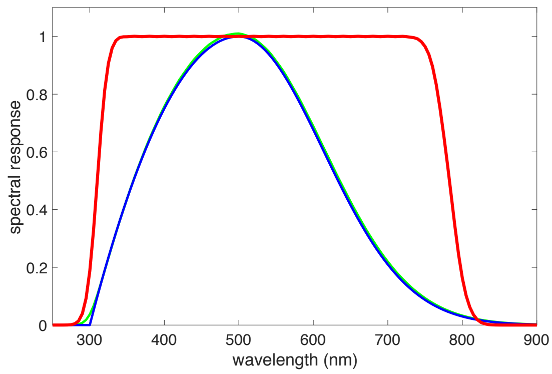

Figure 2. The solid red curve is an approximation to a constant spectral response from 300nm to 780nm (the assumed useful range for an a-Si PV cells), used for calculating UF. Solid green curve is the spectral response of a typical a-Si PV cell, while the blue curve is the estimated spectral response obtained using a weighted sum of the responses of 30 evenly spaced 20nm width Gaussian sensors, used for calculating WUF.

The results in Figures 2 and 3 suggest that summing the responses of 30 sensors (20-nm width Gaussian sensors, from 300nm to 900nm every 20nm) can give a very good estimate of the spectral response of an a-Si PV cell. The accuracy of the summed response can be obtained by calculating quantities such as the UF, WUF and APE using both the spectral response of the a-Si cell and the approximation obtained by summing the sensor responses. However, this leaves the question of the target accuracy.

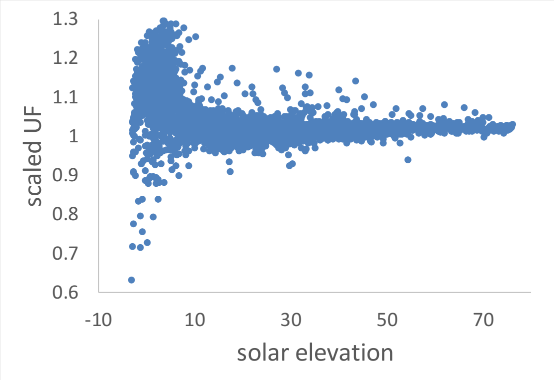

Figure 4. Scaled UF of the whole dataset as a function of solar elevation.

Analysis of our data set, Figure 4, shows that for the spectra that it contains, the UF varies by up to 20%. This suggests that a target accuracy of better than 1% would detect the larger changes in UF. In addition, the efficiency of an a-Si PV cell changes by 0.1%/K, and since the temperature of the PV cells won't be controlled an accuracy of better than 0.1% might be superfluous. A target estimation error of between 0.1% and 1% would therefore seem reasonable.

The final factor that has been taken into account in this work is the impact of noise. In particular, a noise level of 1%, equivalent to a SNR of 40dB, has been added to the data in the simulations. However, in an attempt to determine the accurate of the proposed method regardless of noise results have also been obtained using noise-free data.

4 RESULTS

As we showed in Figures 2 and 3, the responses of a set of sharp (20nm width) equally spaced Gaussian sensors can be added together to estimate the spectral responsivity of a typical a-Si cell, or a bandpass filter in the range of interest of that cell (necessary to estimate the total integrated irradiance for UF calculations). This means that it is possible estimate the UF, WUF, or the APE from the responses of the sensors in our system, without using spectral estimations as an intermediate step. In the case of UF and WUF, sensors up to 900nm approximately are necessary because their tails have some sensitivity in the a-Si range (300nm to 780nm). However, in the case of the APE, we are interested in the average energy taking into account the whole range between 300nm and 1100nm. Hence, a bigger number of sensors is necessary for estimation of this metric (shown in Table 2).

Table 1 contains the average and standard deviation error in the estimation of the UF and WUF (Table 2 shows the results for APE) for the case of a typical a-Si cell, expressed in percentage, for a SNR of infinity and a more realistic one assuming an SNR of 40dB. Unsurprisingly, the mean error in these tables represents the error in the integrated area under the spectral curves of the a-Si cell (in the case of WUF) or the band-pass filter (in the case of UF) made by approximating these curves with our weighted sum of sensor responses. For this reason, the mean error shown in the tables is independent of noise, and only depends on the number of sensors used to approximate the curve of interest by a weighted sum of Gaussian sharp sensors. This constant offset could then be easily corrected. Hence, the standard deviation should be taken as a representative metric for the error of our direct method in estimating the metrics of interest.

These results show that the responses from sets of Gaussian sensors with a FWHM of 20nm can be used to estimate the UF, WUF and APE to an accuracy of better than 1% if enough number of sensors is used. However, for this potentially cost sensitive application it is important to use the fewest possible sensors. Unfortunately, as the number of sensors is reduced the errors increase rapidly and consequently when there are only 8 sensors the errors have increased approximately by a factor of 10 compared to the case with 30 sensors.

Filters sampling the a-Si range	SNR	%error UF (mean & StDev)	%error WUF (mean & StDev)
30	Infinity	-0.45 & 0.06	-0.27 & 0.04
	40dB	-0.45 & 0.30	-0.27 & 0.32
24	Infinity	-1.9 & 0.10	-1.7 & 0.08
	40dB	-1.9 & 0.43	-1.7 & 0.63
15	Infinity	-10 & 0.31	-10 & 0.31
	40dB	-10 & 0.92	-10 & 2.00
8	Infinity	-17 & 0.94	-17 & 1.60
	40dB	-17 & 2.10	-17 & 3.30

Table 1. Accuracy of the direct method estimating UF and WUF for various numbers of 20nm-width sensors and two levels of signal-to-noise ratio.

Filters sampling the 300-1100nm range	SNR	% error APE (mean & StDev)
40	Infinity	0.0 & 0.02
	40dB	0.0 & 0.12
30	Infinity	1.7 & 0.04
	40dB	1.7 & 0.42
20	Infinity	2.0 & 0.90
	40dB	2.0 & 0.58
10	Infinity	2.8 & 0.46
	40dB	2.8 & 1.10

Table 2. Accuracy of the direct method estimating APE for various numbers of 20nm-width sensors and two levels of signal-to-noise ratio.

Previously the Imai-Berns method has been successfully used to estimate the spectrum of daylight from the responses of a limited number of sensors. This method has therefore been used to estimate the spectrum of the light falling on the sensors which can then be used to calculate the UF, WUF and APE. In addition, having spectral information of the radiation impinging on the cells permits to estimate the photon absorption rate (PAR), calculated as shown in Equation 2 (where h is Planck's constant and c is the speed of light).

$$PAR = \int_{300nm}^{1100nm} E(\lambda)SR(\lambda)\,\frac{\lambda}{hc}\,d\lambda \qquad (2)$$

which is proportional to the short circuit current that would be obtained from a PV cell with a spectral response SR(λ).

Figures 5 to 8 show the standard deviation of the percentage errors in these four parameters when the Imai-Berns spectral estimation method had been developed using 100 spectra chosen to represent the entire data set as a training set. In all cases shown, the number of used eigenvectors equals the number of sensors, since this approach have proven to provide optimum results [7]. As expected, the errors in the estimates obtained using this method increase as the number of sensors is reduced. However, using the limited data available from the sensors to first estimate the spectrum of the light irradiating the sensor, significantly improves the results that are obtained when the number of used sensors is smaller than 15. For example, when using data from 15 sensors using spectral estimation before calculating the parameters, reduces the errors in the estimates by half, approximately.

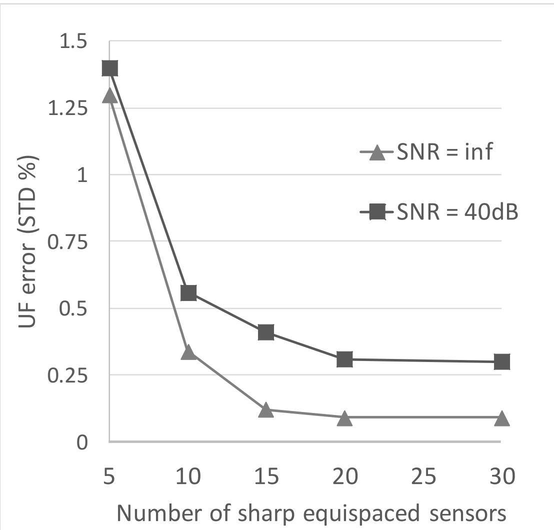

Figure 5. The UF from the Imai-Berns method for varying numbers of sensors.

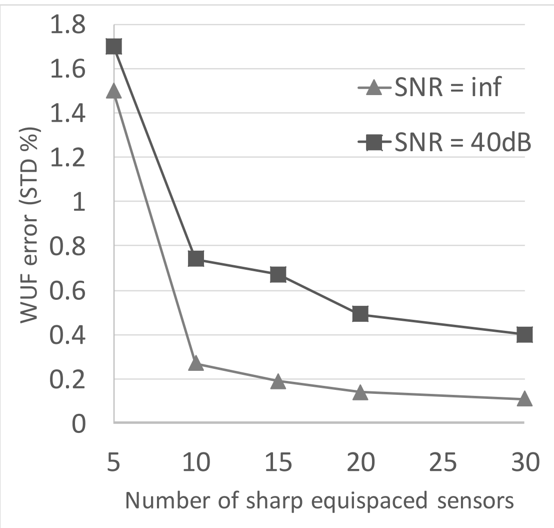

Figure 6. The WUF from the Imai-Berns method for varying numbers of sensors.

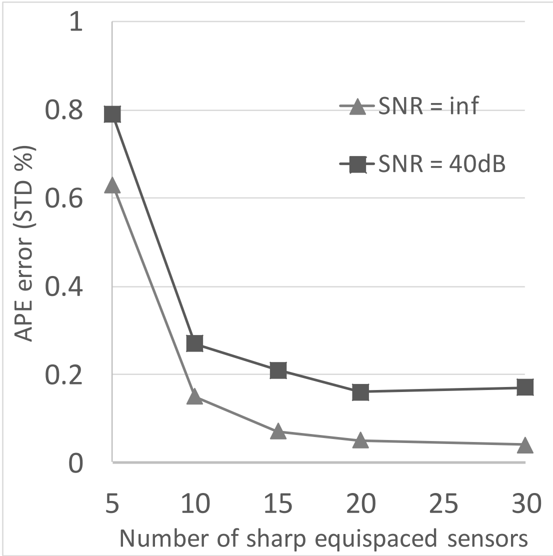

Figure 7. The APE from the Imai-Berns method for varying numbers of sensors

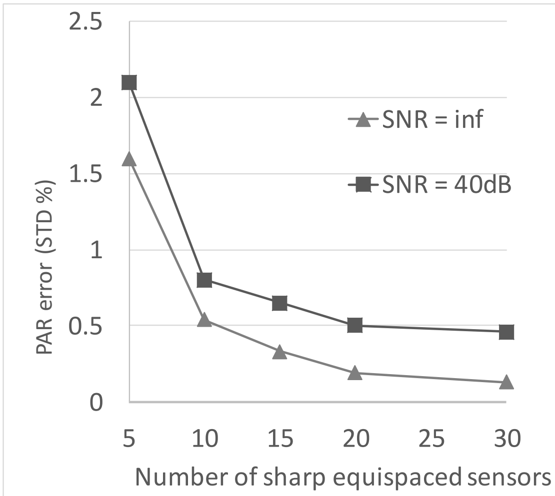

Figure 8. The PAR from the Imai-Berns method for varying numbers of sensors

5 CONCLUSIONS

Having real-time knowledge of the spectrum of the radiation impinging on a solar cell could be a useful part of an efficient maximum power point tracking system that maximized the performance of a PV system under partial shading conditions. We have shown that the spectral distribution of the available daylight in Granada is variable enough to have a significant impact on the performance of a PV cell. In particular, data gathered over two years, showed that the useful fraction, previously used to explain changes in PV cell efficiency, can vary up to 20%. Using these data, we have shown how a potentially inexpensive system, based on a small number of sensors made using a new process that allows the integration different Fabry-Perot filters onto individual photodetectors on the same silicon substrate, can provide accurate estimates of UF, WUF, APE or PAR metrics. Two different approaches have been compared: direct estimation of the PV cell responsivity from the combination of equally spaced sensors with different spectral responses, and calculating these parameters after first estimating the spectrum of the light falling on the sensor. The first approach is good enough to determine the UF and WUF parameters to an accuracy of less than 0.32% in realistically noisy situations. By using the Imai-Berns method to estimate the spectrum of the illuminating light before calculating the parameters of interest, this accuracy can be achieved with a reduced number of sensors (around 20 instead of 30). We can additionally calculate the rate at which photons will be absorbed, which is related to the short circuit current of the PV cell whose spectral response is being estimated.

The results that have been obtained suggest that a recently commercialized sensor technology could be used to sense the intensity and spectrum of light falling on each module in a PV system. This information could then be used to determine which of the possible maximum power points will be the global power point at a particular instant. Further work is required to determine how these sensors might be distributed within a set of PV modules, the number of sensors, and hence cost, required to obtain the information required by the MPPT system, and the potential benefits of using sensors to both reduce the time needed to find a global maximum power point and eliminate the need to frequently check if the current operating conditions are the optimum conditions.

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7 ACKNOWLEDGEMENTS

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