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A NOVEL SHADING ANALYSIS METHOD FOR PV SYSTEMS USING SUN PATH PLOTS AND HIGH RESOLUTION PERFORMANCE DATA

S. Firth, S. J. Rees and K. Lomas
Institute of Energy and Sustainable Development, De Montfort University, Leicester, LE1 9BH, UK
tel: +44 (0)116 257 7962, fax: +44 (0)116 257 7977
email: sfirth@dmu.ac.uk

ABSTRACT: This paper presents a technique for identifying and quantifying shading losses in PV systems. Five minute interval monitored data from domestic UK PV systems is used to assess the effects of trees and other shading objects on annual energy generation. Poor performance is identified from the relationship between in-plane irradiance and performance ratio. Shading events are identified by plotting the occurrences of poor performance on a 'sun path plot' of solar azimuth and elevation axes. Poor performance which concentrates about particular sun positions is identified as shading. Once identified, the energy loss due to shading is quantified.
Keywords: Shading, Performance, Monitoring

1 INTRODUCTION

Monitoring of PV systems is essential in building confidence in the technology. PV system monitoring involves taking on-site measurements during operation and analysing the recorded data to evaluate the system performance. Energy generation and efficiency values are calculated and used to illustrate the actual performance of the PV system compared to expectations. Monitoring is also used to quickly identify operational faults and reduce the energy lost through system failure.

There has been much research in PV system monitoring. Studies have shown the measured performance for a wide variety of systems [1] and a consensus on the performance of a well-operating PV system has been established (annual performance ratio of 70 – 80 %). These studies are typically based on monthly or annual data. The approach can highlight when a system is performing poorly but it struggles to identify the reasons for poor performance.

More detailed studies use data with shorter time intervals to analyse system performance. Pearsall and Hynes [2] use five minute data to identify poor performance due to shading and inverter problems but do not quantify the losses. Oozeki et al. [3] assesses performance from hourly datasets and calculates the energy lost due to shading and incidence angle reflection. Both of these methods require the data to be divided into short time periods and analysed on a day by day or month by month basis. This approach is potentially time consuming for many datasets.

This paper introduces a new technique for PV system performance analysis based on high resolution (five minute interval) data analysed over large time periods (a year or greater). All of the data is analysed at once and the technique both identifies and quantifies system performance and losses. This provides a near real-time assessment of the system operation. To demonstrate this method of analysis, a case study is described in this paper based on an apparently heavily shaded PV system and the effect of the shading is discussed.

2 THE PV SYSTEM

As part of the UK Governments Photovoltaic Domestic Field Trial (DFT) Programme [4], over 100 UK domestic PV systems were monitored for a two year period. Meteorological data (solar radiations and temperatures) and system data (DC energy form the array and AC energy form the inverter) were recorded every five minutes for each PV system. This high resolution data allows the operation of the PV systems to be studied in near real time detail. This study uses only two of the monitored parameters, the in-plane solar irradiance (in W/m^2) and the AC power output from the inverter (W). A schematic of the monitoring setup is shown in Figure 1.

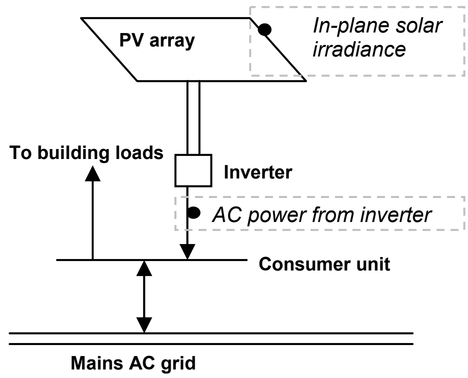

Figure 1: Schematic of PV system monitoring

Figure 2: The shaded PV system (the array on the left) with the surrounding trees and pitched roof

This paper focuses on one of the PV systems being monitored, the shaded PV system shown in Figure 2. The PV system has a rating of 1.53 kWp and faces 15° west of due south. The PV modules are connected in series to a single inverter. The system has two large deciduous trees surrounding it, one slightly east of due south and the other to the south-west. The system also has a raised pitched roof to the west. Performance data was collected from the PV system at five minute intervals over a two year period. The monitored data from the PV system was studied to investigate the possible shading effects of these external objects on the overall energy generation.

3 IDENTIFICATION OF POOR PERFORMANCE

Values of performance ratio are calculated for each five minute time interval over the two year monitoring period. Performance ratio is the ratio of the PV system efficiency to the nominal efficiency of the modules at standard test conditions. The nominal efficiency is a constant value and performance ratio is proportional to the overall system efficiency. Figure 3 shows the five minute values of measured in-plane solar irradiance plotted against calculated performance ratio values for the PV system over the two years of operation.

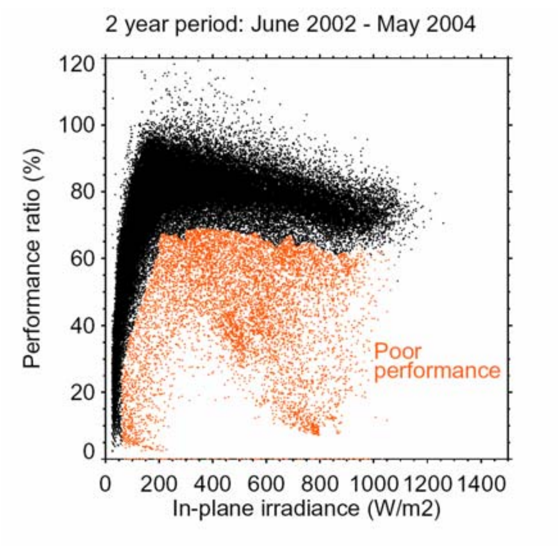

Figure 3: In-plane irradiance vs. performance ratio (five minute interval values) for the PV system over a two year period. Low performance ratios throughout the range of irradiance are identified as poor performance and shown in red.

The majority of the performance ratio values follow a curve rising from 0 % at zero irradiance to around 80 % at irradiance above 200 W/m^2. The decrease in performance ratio as irradiance increases above 200 W/m^2 is due to higher PV module temperatures. The shape of the main curve matches the efficiency vs. irradiance curves of PV cells or modules [5, 6] and represents the PV system operating under normal conditions. The scatter of points on the curve is due to the variety of losses present in PV systems, mainly temperature variation and inverter tracking.

It is clear from Figure 3 that some of the performance ratio values do not fall on the curve and instead lie above or below it. Points that lie above the curve may be occurrences of measurement or recording error, such as instances when the radiation sensor under records in-plane irradiance. Points below the curve have low or zero performance ratio throughout the range of irradiance when the majority of the performance ratio values are high (around 80 % above 200 W/m^2). These points represent times when the system is not operating as expected and are defined as points of *poor performance*.

The relationship between performance ratio and in-plane irradiance shown in Figure 3 can be described as a series of normal distribution curves. The points are divided into irradiance bins and for each bin the performance ratio distribution is calculated. Figure 4 shows the performance ratio distribution for irradiances between 500 and 525 W/m^2. The performance ratio distributions approximates the normal distribution and a normal distribution curve is fitted to the performance ratio distribution using a least-squares fitting technique. Poor performance values are defined using the fitted normal distribution as points less than 2.5 standard deviations below the mean. At low irradiance, below 250 W/m^2, the distributions become less normal and five standard deviations below the mean is used to identify poor performance. These values were chosen through inspection of multiple PV system curves. By repeating this technique for all irradiance bins, poor performance for all levels of irradiance can be identified (as shown in Figure 3).

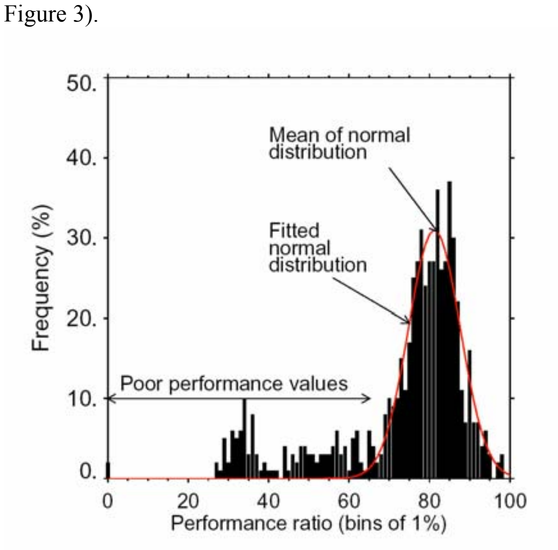

Figure 4: Fitted normal distribution curve to performance ratio distribution within irradiance bin 500 – 525 W/m^2. Poor performance is identified as points less than 2.5 standard deviations below the mean.

4 IDENTIFICATION OF SHADING

4.1 Overview

Shading is a cause of poor performance of PV systems and can result in a reduction in energy generation. Shading reduces the power output of PV modules and even slight shading of a module can dramatically reduce the output power. The PV system under study had a number of external objects which appeared to be causing shading. The monitored data was analysed to establish the effect of this shading.

Shading is often considered as a function of time of day and time of year. Shading is more likely to occur in the winter months when the sun is lower in the sky. However shading can more accurately be defined as a function of sun position. If the shading is being caused by external objects, and these objects do not move, then shading will occur when the objects block the direct beam solar radiation between the sun and the PV array. This depends on the position of the sun (as position of the PV array and external objects are fixed) and similar sun positions are likely to have similar shading effects.

4.2 Performance ratio sun path plot

Sun position is defined by the solar azimuth α (bearing from due south where east is positive and west is negative) and solar elevation β (angle between the sun and the horizon). A plot of the sun position using solar azimuth and solar elevation axes for June – December 2003 is shown in Figure 5. The position of the sun at each five minute interval throughout this period is marked by a false colour point (only sun positions for irradiances above 50 W/m^2 are shown to exclude night time values). The colour of the points represents the value of the performance ratio which occurs at that instance. Blue indicates times of low performance ratio and yellow times of high performance ratio. This type of plot is referred to as a 'sun path plot' in this work.

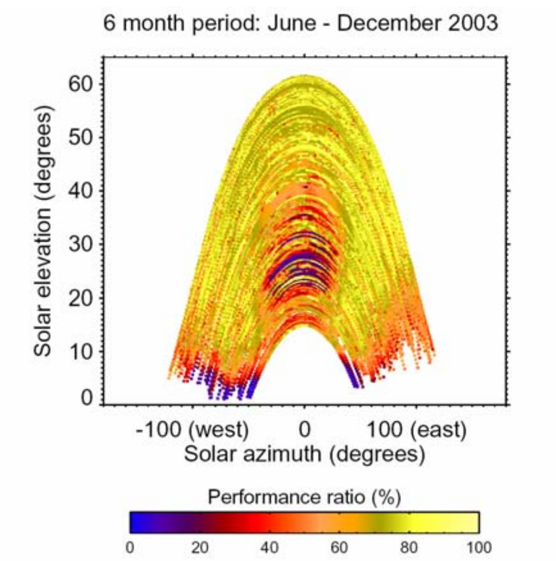

Figure 5: Sun path plot of performance ratio on solar azimuth and solar elevation axes for the PV system from June to December 2003

The sun path plot in Figure 5 consists of a series of curves that describe the daily movement of the sun. Throughout each day the sun moves from east to west and transverses an arc in the sky. The longest arc and the highest solar elevation occur on June 21st and the shortest arc and lowest elevation on December 21st. As expected, at the beginning and end of each day the performance ratio is low due to the low irradiance levels that occur at sunrise and sunset. Throughout the remainder of the day in summer the performance ratio is usually around 70 – 80 % and the system can be said to be operating normally. However in autumn, winter and spring there is consistent low performance ratio in the middle of the day (at $-50° < \alpha < 50°$ and $\beta < 45°$).

This concentration of low performance ratio at similar sun position suggests that shading is occurring. Study of the on-site geometry shows that the large tree to the south of the PV array is causing the shading and the outline of the tree can be seen in Figure 5. When this analysis is repeated for December 2003 to June 2004 a smaller shading effect is observed, because the leaves of the tree are smaller in spring than in autumn.

4.3 Poor performance sun path plot

To investigate the effect of the shading seen in Figure 5 on the energy generation of the PV system, a similar analysis is carried out using the points of poor performance. Poor performance is identified using the technique described in Section 3 and is plotted on a sun path plot. Figure 6 shows the poor performance sun path plot for the PV system over the two year monitoring period. The poor performance points concentrate at low solar elevations and in the middle of the day in autumn, winter and spring months.

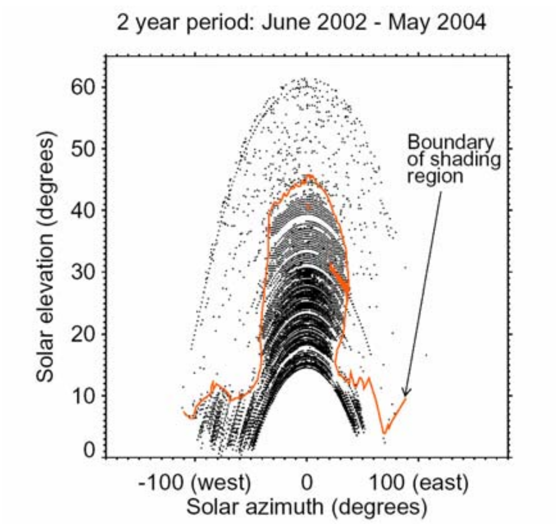

Figure 6: Sun path plot of the points of poor performance for the PV system over 2 years from June 2002 to May 2004. The region of shading is identified by the boundary line shown in gray.

It is assumed that shading will cause a concentration of poor performance points about similar sun positions as the external shading objects are stationary. A procedure has been developed to automatically detect high concentrations of poor performance in plots such as Figure 6 in order to identify times of shading. For each poor performance point with sun position α_0 and β_0 a region of sun position $-5° < \alpha_0 < 5°$ and $-2.5° < \beta_0 < 2.5°$ is considered. The total number of poor performance points in this region is used to assess if there is a high concentration of poor performance about sun position α_0 and β_0. Inspection of a number of sun path plots has shown that when the concentration of poor performance points in the region about a particular sun position is greater than 10 % of the total number of sun positions in the region then this suggests that shading is occurring. The 10 % concentration limit is used to identify poor performance due to shading and to calculate the boundary of the shading region as shown in Figure 6.

The remaining poor performance which is not identified as shading does not appear to have a correlation with sun position. This poor performance occurs mainly in the summer months at seemingly random sun positions and is assumed to be caused by inverter failures and other events.

This novel shading analysis technique presented here has been validated using a three dimensional geometric model of the site. The array is modeled as a mesh of 100 points and the surrounding trees and objects are created as objects. Ray tracing procedures estimate the percentage area of the PV array under shade for each sun position through the year and the results match the shading identified in Figure 6.

5 QUANTIFICATION OF SHADING EFFECT

Once shading has been identified, using the techniques described in Section 4, the amount of energy lost due to shading can be quantified. Energy loss is calculated by considering the difference between the performance ratio of poor performance occurrences due to shading and the estimated performance ratio if the PV system had not been shaded. Unshaded performance ratio is estimated from the means of the normal distributions defined in Section 3 and is described by the curve of the majority of the points in Figure 3. For example, if a poor performance point occurs at irradiance of 500W/m^2 and performance ratio of 50%, it is assumed that the unshaded performance ratio would have been 80 % (the mean of the normal distribution in Figure 4) and the difference in performance ratio 30 %. The differences in performance ratio are used to calculate the energy lost due to shading.

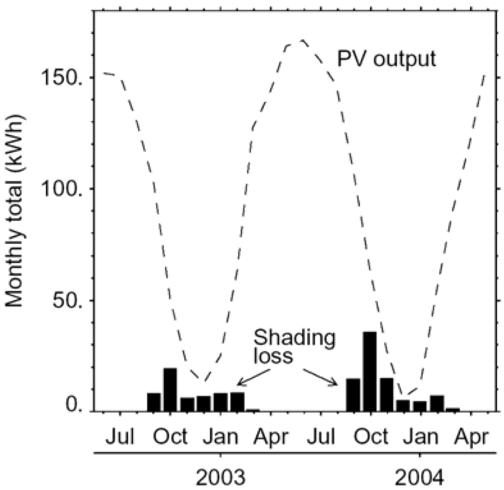

Figure 8: Monthly totals of PV generation output and energy lost due to shading for the PV system over the 2 years of operation

Figure 8 shows the monthly totals of PV generation output and energy loss due to shading for the PV system over the two years of operation. Energy loss due to shading occurs from September to March. Although the sun path plot (Figure 6) suggests that shading has the most effect in the winter months, the most energy lost due to shading occurs in autumn (with a peak in October). There is more solar radiation available in autumn than in winter, so more energy can be lost if shading occurs. Moreover the leaves on the trees are at their largest in autumn causing a larger shading effect. Shading in spring is much lower than in autumn because of the smaller size of the leaves on the trees.

The total energy output by the PV system over the two year monitoring period is 2250 kWh (equivalent to annual final yield of 735 kWh/kWp). The energy lost to shading over this period is calculated as 142 kWh which represents a 6 % loss in energy generation due to the effects of shading. The relatively small effect on overall energy generation can be accounted for by the fact that shading is not present in summer when the bulk of the PV system energy generation occurs.

6 CONCLUSIONS

A novel shading analysis technique for PV systems has been described, based on high resolution monitored data. The technique is illustrated through a case study of a UK domestic PV system. Poor performance is identified through an investigation of the relationship between in-plane solar irradiance and performance ratio. Sun path plots (based on the sun position throughout the monitoring period) are used to identify when shading occurs and the energy loss due to shading is quantified. This technique combines the analysis of high resolution (short time interval) data and large datasets (monitored over a time period of year or greater).

This work is continuing with an analysis of inverter behaviour in the PV systems. Further work is also being conducted using household consumption data to investigate the relationship between the supplied PV electricity and the load profiles of the houses.

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