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Irradiance modelling for individual cells of shaded solar photovoltaic arrays

Brian Goss *, Ian Cole, Thomas Betts, Ralph Gottschalg

Centre for Renewable Energy Systems Technology (CREST), School of Electronic, Electrical and Systems Engineering, Loughborough University, LE11 3TU England, United Kingdom

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Abstract

Developments in Photovoltaic (PV) design software have progressed to modelling the string or even the module as the smallest system unit but current methods lack computational efficiency to fully consider cell mismatch effects due to partial shading. This paper presents a more efficient shading loss algorithm which generates an irradiance map of the array for each time step for individual cells or cell portions. Irradiance losses are calculated from both near and far obstructions which might cause shading of both beam and diffuse irradiance in a three-dimensional reference field. The irradiance map output from this model could be used to calculate the performance of each solar cell individually as part of an overarching energy yield model. A validation demonstrates the calculation of shading losses due to a chimney with less than one percent error when compared with measured values.

Keywords: Solar; PV; Photovoltaic; Shading; Mismatch; Irradiance

1. Introduction

Developers of solar photovoltaic (PV) systems would benefit from more accurate prediction of energy yield and internal rate of return (IRR). A reduction in prediction uncertainty to within given confidence limits would help secure lower cost financing, contributing to the drive for grid parity in the solar industry. There is a lack of consensus in the industry regarding how much separation should be left between PV arrays and near shading objects such as chimneys and dormer windows. This manifests in anecdotal reports of poorly designed systems with modules heavily shaded by obstructions, where closer attention to design would have made significant improvements to energy yield. Mismatch effects of shading are not normally considered in system modelling because the computation time would be too great.

Shading can be the most detrimental factor on performance for a domestic system. The impact of shading on performance varies depending on the electrical series and parallel arrangement of cells within a module and modules within an installed array. Whilst many approaches to shading analysis have been proposed, computational efficiency is not reported despite being of high importance when incorporating shading algorithms into an overall energy yield model. The lack of consideration of the non-linear impacts of shading on smaller systems for example means that the shading loss is significantly underestimated, especially from supposedly small obstacles such as antennas or chimneys. As an example, the system shown in Fig. 1 illustrates the case where the installer may have attested a

* Corresponding author. Tel.: +44 (0)7771 743724.
E-mail address: b.goss@lboro.ac.uk (B. Goss).

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Nomenclature

a_s area of the segment of the spheres surface
d distance from point on the horizon to cell
Gbk Global beam irradiance
Gdk, h, a Global diffuse irradiance
i sideways cell index
j upwards cell index
$L_{D,I,J}$ diffuse loss factor for cell with position I, J in the array
n number of sky-patches
p sideways spacing between cells, in 3D Cartesian space
q vertical spacing between cells, in 3D Cartesian space
r front to back horizontal spacing between cells, in 3D Cartesian space
s sideways sky-patch index
t upwards sky-patch index
R_X sky-dome resolution in the X (azimuth) axis
R_Y sky-dome resolution in the Y (elevation) axis
s spacing between cells in 2 dimensional space
SP_{st} Sky-dome of cell i, j
x east–west position of horizon point relative to cell
y upwards position of horizon point relative to cell
y north–south position of horizon point relative to cell

Greek letters
α_a azimuth angle of PV array,
α_B azimuth angle of point on arc behind PV array,
α_H azimuth angle from cell to horizon point,
α_P azimuth angle of sky patch,
α_S azimuth angle of sun,
d distance from cell to horizon point.
ε_A angle of tilt of the PV array
ε_H elevation angle of a point on the horizon (from cell).
ε_P elevation angle of sky patch
ε_T elevation angle of test horizon
ε_B elevation angle of a point on an arc where an infinitely large array would intersect the sky-dome
θ zenith angle between the horizon point and the z axis to
ρ radius of test horizon sphere

shade loss factor close to unity under UK microgeneration guidelines (Microgeneration Certification Scheme, 2013), i.e. negligible, but the performance of the system is severely compromised due to the non-linear cell mismatch effects. An effective shading sub-model therefore needs to give feedback to inform decisions of array layout in the proximity of obstructions but must not rely on high power computing.

The algorithms to calculate shading losses within an overall PV system energy yield model can be divided into two main sub-models:

Fig. 1. Photograph showing a south facing PV-system which is not heavily shaded but the energy yield loss due cell mismatch is significant.

(a) The shaded irradiance sub-model – which calculates irradiance incident on the cells, using spatial location data for shading objects.
(b) The array electrical sub-model – which calculates current & voltage for each string, taking mismatch into consideration using cell irradiance calculated in the shaded irradiance sub-model (Bishop, 1988; Quaschning and Hanitsch, 1996; Overstraeten and Mertens, 1986; Liu et al., 2011).

This paper is concerned primarily with the shaded irradiance calculation, the output of which can be interfaced with any electrical mismatch model. Shaded irradiance models fall into two main categories, those which view

(a) The surface from the point of view of the sun.
(b) The sky from the point of view of the surface.

Models in category (a) commonly use rendering to generate a three dimensional view of a building or district, with shading used to indicate zones of varying irradiation. (Mardaljevic and Rylatt, 2003; Compagnon, 2004; Levinson et al., 2009; Lukač et al., 2013). A key challenge of this approach is the computation time to model irradiance for each surface segment and for each hourly sun position. A logical optimisation is to bin sun positions into zones of similar irradiation, for example from 4000 hourly sun positions above the horizon into 250 bins (Mardaljevic and Rylatt, 2003). This approach is typically used in