Applied Energy 144 (2015) 1–9

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimal displacement of photovoltaic array's rows using a novel shading model

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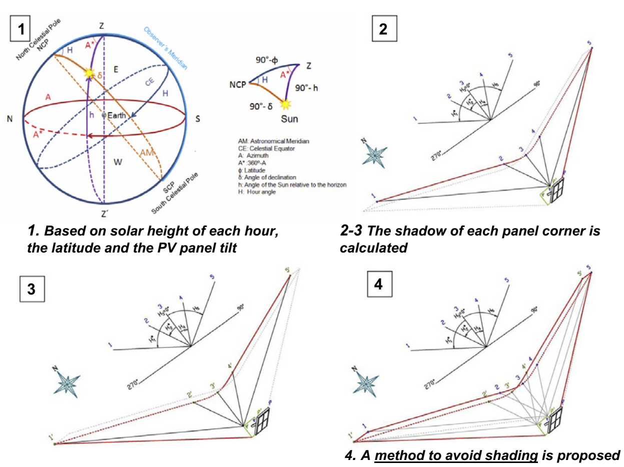
HIGHLIGHTS

- Photovoltaic energy has experienced tremendous growth worldwide.
- The position of the fixed panels presents the problem of shadowing among them.
- A method to avoid shading is proposed.
- The method is based on solar height, the latitude and the PV panel tilt.
- Results indicating that the proposed method can reduce the area by up to 40%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form 13 January 2015
Accepted 15 January 2015
Available online 4 February 2015

Keywords:
PV panel
Panel arrays
Photovoltaic
Shadow
Optimization
Sizing

ABSTRACT

Photovoltaic energy has experienced tremendous growth in terms of implementation at facilities for power supply in rural areas and for energy dispatch to grid. The relative position of the fixed panels can present the problem of varying amounts of shadowing among them, which can reduce the overall energy produced from the array of photovoltaic panels on specific dates and times, in addition to the problems in each of the panels themselves. The existing methods calculate the distances between the rows of PV panels using a fixed height of the sun, such that the rays always strike perpendicular to the panels, thereby limiting the duration of solar gain to 4 h. This paper proposes a method that optimises the minimisation of the distance between the rows of fixed photovoltaic panels. The proposed method is based on the exact calculation of the shadows of the panels for the different positions of the sun, which depends on the latitude of the facility, throughout the course of the day and for all of the planned hours of solar gain. To illustrate the proposed method, it has been applied to a case study for which the solutions obtained using the traditional methods are compared, indicating that the distance can be reduced by up to 40% when the tilt angle of the panel is 60°. In conclusion, the proposed general method for optimally minimising the distance between the PV panels in solar arrays, which is of particular interest for stand-alone photovoltaic (PV) systems in remote areas that act as isolated small power producing units for the supply of electricity.

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http://dx.doi.org/10.1016/j.apenergy.2015.01.060

Nomenclature

A	azimuth of the sun	PV	photovoltaic
A^*	360-A	PV_1	first row of PV panels
d	separation between the modules	PV_2	second row of PV panels
d_i	distance plan of the shadow of the point i	PV_{2h}	second row of PV panels depending on the sun angle h
D	length of the shadow cast by a module	w	PV panel width
h	angle of the sun with respect to the horizon	α	azimuth of the panel
H	hour angle of the sun	β	angle relative to the horizontal PV panel
H^*	360-H	δ	declination of the Earth
H_i	hour angle of the point i	θ_{ZS}	zenith angle
k	dimensionless factor depending on the latitude of the location	Φ	latitude
ℓ	high PV panel	γ_s	solar altitude angle

1. Introduction

Energy is a vital input for social and economic development [1]. The demand for energy is expected to increase at a faster rate in upcoming years [2], partly due to the exponential growth of the world's population [3]. The World Bank and International Energy Agency (IEA) estimated that the world will require a doubling in installed energy capacity over the next 40 years to meet the anticipated demands of developing countries [4]). The realisation that the fossil fuel resources required for the generation of energy are becoming scarce and that climate change is related to carbon emissions to the atmosphere has increased interest in energy savings and environmental protection by reducing the use of fossil fuels [5]. One strategy to achieve the goal of reducing the dependence on fossil fuel resources involves the use of renewable energy sources, not only for large-scale energy production but also for stand-alone systems [6].

In response to concerns of environmental pollution, solar energy is playing a leading role in reducing the environmentally hazardous gasses produced during conventional electricity generation [7]. Photovoltaic solar systems are projected to prevent 100 Gt (Gigatons) of CO_2 emissions during the period from 2008 to 2050 [8]. Photovoltaic (PV) technology is one of the first among several renewable energy technologies that was adopted globally for meeting the basic electricity needs of rural areas that are not connected to the grid [9].

The installation of PV systems have played an important role worldwide because they are clean, environmentally friendly and secure energy sources [10].

During the last few years, photovoltaic solar systems have become one of the most popular renewable energy sources in Europe [11], particularly in Spain [12]. PV systems represented 16% of all new power capacity installations in Europe in 2009 [13].

Generally, the works related to the sizing of the PV panels are focused on the following: (1) the dimensions of the surface of each of the panels to meet an energy requirement [14] or to optimise the costs of the PV system, which includes the photovoltaic panels, a battery bank, a battery charger controller and an inverter [15], or (2) optimizing the Life Cycle Cost, LCC, which must be minimised [14]. When the photovoltaic cells were selected and the number of solar panels installed at a certain angle were determined, the PV array spacing becomes the most critical issue [16].

In photovoltaic (PV) systems, the solar cells are often connected in series, one completely shaded solar cell will act as loads, so draining power from fully illuminated cells and reducing the output of the whole string. In addition, it reduces array efficiency and causes hot-spot heating, a faulty mode of operation which can damage cell encapsulation materials, permanently reduce array power output and even put arrays out of action [17]. Although bypass diodes can be used to mitigate this effect by allowing current to flow in a different path, they increase both assembly time and material cost which lead to increased costs. This area has been and is still attracting immense interest from PV research communities as well as industrial players because it is the most economical way to improve the overall PV system efficiency [18].

Scientific communities have studied mainly the calculation of partially shaded conditions (PSCs) that often occur in large photovoltaic generation systems (PGSs). PSCs cause losses in system output power, hot spot effects, and system safety and reliability problems [19,20]. Deline et al. [21] focused their study on the performance impact of partial shading on a large PV system. Goss et al. [22] studied the algorithms to calculate shading losses within an overall PV system energy yield model for two sub-models: irradiance incident on the cells and current and voltage (I–V) for each PV device.

To completely avoid shading, the methods found to resolve this issue in the literature, which will be described later (Section 2), are limited by the number of hours of solar gain or are based on either a fixed angle of the sun or on empirical equations that are not useful worldwide. This paper proposes a method of determining the distance between fixed PV panels without limiting the useful hours of energy production, for any angle of the sun and for any latitude, thereby enabling the method to be applied anywhere. To validate the proposed method, a comparison with traditional methods will be made for a case study that represents the major energy production situations of a photovoltaic system.

2. Installation of photovoltaic panels: a brief review and mathematical modelling

The designs of photovoltaic panels systems are optimised to obtain the maximum energy efficiency. In the traditional design process, the surface of the solar panels is assumed to be perpendicular to the path of the incident sunlight. Due the terrestrial declination, the relative position of terrestrial hemispheres constantly varies relative to the sun throughout the year. Therefore, to achieve the above perpendicularity of the solar rays to each PV panel, the inclination of the panels relative to the horizon must vary over the year. If the installation is fixed, a solution to maximise the energy production is to have the solar panels placed in the position as perpendicular as possible to the sun during the winter solstice.

The true twelve hours of the solar day (time of the zenith passage of the sun or the meridian of the place), establish the relationship between the declination (δ), latitude (Φ) angle and height of the sun on the horizon (h), which is given by the equation [23]: