Applied Energy 187 (2017) 326–337

Contents lists available at ScienceDirect

Applied Energy

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

PV array power output maximization under partial shading using new shifted PV array arrangements

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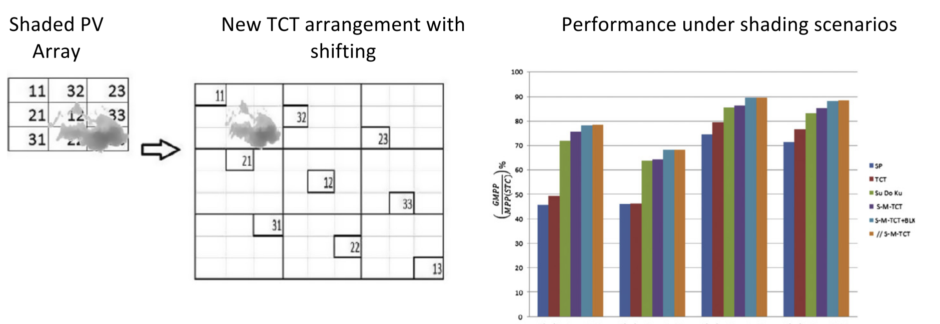
HIGHLIGHTS

- New physical PV array arrangements are proposed to mitigate partial shading effects.
- Performance analysis performed under a range of cloud and shading pattern scenarios.
- Shifted PV arrangements power-voltage curves exhibit a single peak.
- Global Maximum Power Point is readily determined.
- Power dissipation is reduced and energy output is optimized.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form 29 October 2016
Accepted 11 November 2016

Keywords:
Photovoltaic (PV)
Partial shading effects
Bypass and blocking diodes
PV array configuration
Maximum power point tracking (MPPT)
Solar energy

ABSTRACT

Partial shading can dramatically reduce the power output of a PV array as well as complicate operation by causing multiple peaks to appear in the power-voltage (P-V) characteristic curve. The extent of these problems depends not only on the shading area but also and much more significantly on the shading pattern. In this paper three new physical PV array arrangements are proposed to mitigate partial shading effects. The arrangements are based on maximizing the distance between adjacent PV modules within a PV array by appropriately arranging modules in different rows and columns without changing the electrical connections. A systematic analysis is performed to assess the proposed PV array arrangements under different shading patterns and scenarios, and to compare performance with existing configurations. The new arrangements are shown to effectively (i) redistribute shading patterns over the entire PV array, (ii) minimize protection diodes power dissipation, (iii) eliminate multiple peaks, and (iv) maximize power output. The analysis considers shading scenarios related to cloud shape, size, transmissivity and passage over an array. The new configurations simplify operation and improve performance significantly compared to the reference Series-Parallel (SP) and Total Cross Tied (TCT) configurations: the characteristic P-V curves exhibit a single peak allowing tracking of the maximum power point with a simple controller removing the need for complex controller algorithms and costly hardware, and the power output gains range from 19 to 140% compared to SP, and 13 to 68% compared to TCT.

1. Introduction

Solar power generation is growing fast in many parts of the world [1,2] driven by cost reduction, economic incentives and

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http://dx.doi.org/10.1016/j.apenergy.2016.11.038
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the needs for meeting growth in electricity demand while reducing reliance on fossil fuels. However, several challenges need to be addressed to allow its effective deployment [3].

The power output of solar photo voltaic (PV) arrays, the focus of this paper, is optimal only under full irradiation conditions. Under partial shading, solar irradiance and the efficiency of the PV array can decrease dramatically. Shading can be caused not only by clouds, but also by buildings, trees, soiling, dust and even PV cell cracking and ageing [4]. The extent and impact of shading depend on the application and end use, e.g. solar PV power plants, building-integrated photovoltaics, rural electrification or electric vehicles [5,6]. Alleviating the effect of partial shading is an important practical challenge [7].

In addition to reducing the PV array power output, partial shading also causes the power-voltage (P-V) curve to exhibit multiple peaks. This can in turn cause conventional Maximum Power Point Tracking (MPPT) techniques to be trapped at the Local Maximum Power Point (LMPP), which leads to significant power losses. A range of conventional MPPT techniques under partial shading have been devised to address this problem, and their classification, key features and main limitations are reviewed in [8,9]. Notable recent contributions include fuzzy-logic controllers [10], neural-network based methods [11] and sophisticated genetic algorithms to reach the Global Maximum Power Point (GMPP) [12]. Some of the key issues that remain are the complexity and cost of these algorithms, and the need for embedded sensors in some cases [13].

Strategies to mitigate shading effects are based on the observation that shading pattern rather than shaded area is the primary factor determining PV output power losses [14]. A number of researchers have consequently attempted to address the problem using electrical configurations based on interleaving of PV modules [15], and a new research avenue was opened by recent studies showing that partial shading losses can be reduced by modifying the electrical configuration of a P-V array [16,17].

The Series-Parallel (SP) configuration is commonly used in the PV industry, but other PV configurations to mitigate shading effect losses have been reported and include: Bridge Linked (BL), Honey Comb (HC) and Total Cross Tied (TCT) [18]. Although comparative studies have shown the TCT configuration gives the best results in terms of PV Power output for almost all types of shading [19], several researchers still focus their work on partial shading mitigation to the SP configuration [20].

Another configuration modification is the Electrical Array Reconfiguration (EAR) which consists of dynamically changing the electrical connections of PV modules. The main idea in the EAR strategy is to adapt the PV using a controllable switching matrix to select a configuration that reduces as much as possible the partial shading loss for a given shading pattern. This strategy requires a fully reconfigurable array and necessitates sensors and switches that increase system complexity and cost [21–24].

Static reconfiguration is an alternative to EAR that achieves a balance between cost, complexity and efficiency. This approach relies on finding a PV module arrangement with a fixed predefined TCT configuration [25]. The predefined reconfiguration is designed such that the shading effect is minimized for a variety of shading patterns. For example, in [26] a Su Do Ku puzzle pattern is shown to effectively mitigate partial shading and maximize power generation. The Su Do Ku pattern is however only applicable to 9×9 PV modules, and furthermore requires consideration of the impact of protection diodes, especially blocking diodes. PV modules arrangements for arbitrary PV array sizes have been proposed to overcome this limitation [27]. Such arrangements and others discussed in [14,15,25] operate with an array having an equal number of rows and columns, and are restricted to modifying the electrical connections of PV modules which are in the same physical PV array row. As a consequence, shading dispersion is limited and protection diodes power consumption is high. Similar approaches to change the PV module arrangement within a PV array under TCT and other configurations are discussed for example in [28–30]. These arrangements still locate PV modules in the same column and are in fact almost identical to Su Do Ku. In addition, these arrangements have not taken into account the power dissipation of blocking and bypass diodes and, in most cases, have only been applied to small PV arrays.

The brief review highlights the need for improved strategies to deal with the multiple maxima exhibited by the P-V curves, since on the one hand algorithms that avoid trapping at the Local Maximum Power Point (LMPP) and succeed in finding the Global Maximum Power Point (GMPP) are complex and expensive, and on the other hand PV module reconfigurations proposed to date are limited and suffer from various degrees of power dissipation. Here, we present a new reconfiguration strategy that effectively distributes PV modules under shading over the entire PV array. This is achieved with an electrical connection pattern between PV modules that are far apart but not on the same row and/or column. The proposed PV array arrangement leads to P-V characteristic curves that eliminate the LMPPs and exhibit only one easily identifiable peak corresponding to the GMPP. This makes it easier to track the maximum power point with no need for complex MPPT controllers or the added expense of embedded sensors. To further increase the efficiency of the proposed arrangement we also introduce bypass and blocking diodes in each PV module instead of the commonly used blocking diode at the top of a PV array string. This helps reshape the P-V characteristic and effectively ensures one peak even under severe partial shading conditions.

The paper proceeds with a brief overview of the mathematical model of PV arrays and the simulation and analysis of the impact of protection diodes in PV arrays under shading conditions, followed by a description of the new PV array arrangement and a comparative analysis of its performance under a variety of partial shading scenarios.

2. System description

2.1. PV model

A large number of models have been developed to characterize PV modules under varying atmospheric conditions [31]. These models are non linear and rely on a variety of techniques for parameter identification [32,33].

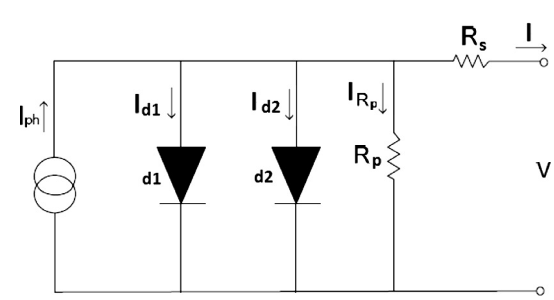

Fig. 1. Equivalent two-diode circuit model of a PV cell.

Table 1
Parameters of MSX-60 PV module.

I_{sc}	3.8 A	K_v	−80 mV/°C
V_{oc}	21.1 V	K_i	3 m%/°C
I_{mpp}	3.5 A	N_{cell}	36
V_{mpp}	17.1 V	P_{max}	58 W