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Adaptive photovoltaic array reconfiguration based on real cloud patterns to mitigate effects of non-uniform spatial irradiance profiles

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ABSTRACT

This paper proposes a simple and dynamic reconfiguration algorithm for photovoltaic (PV) arrays in order to mitigate negative effects of non-uniform spatial irradiance profiles on PV power production. Spatially dispersed irradiance profiles incident on inclined PV module surfaces at each application site are generated based on real sky images. Models of PV modules are constructed in MATLAB/Simulink based on one-diode mathematical model of a PV cell. The proposed dynamic reconfiguration algorithm operates based on irradiance equalization principle aiming for creation of balanced-irradiance series-connected rows of PV modules. The proposed algorithm utilizes an irradiance threshold to obtain near-optimal configurations in terms of irradiance equalization and number of switching actions under any type of non-uniform spatial irradiance profile. The algorithm provides no limits on the number of PV modules within the array. The reconfiguration algorithm is examined with different irradiance profiles and significant improvements, almost equivalent to the ideal case corresponding to equal irradiance for all panels, are achieved for each shading pattern. The advantages of the algorithm are simplicity and providing significant improvements in array's power generation alongside with reduced number of switching actions.

1. Introduction

Solar energy due to its clean and renewable nature outperforms many conventional energy resources and its application areas have significantly been growing during the recent years. The non-linear nature and dependency of this energy source to the incident solar irradiance is one of its main disadvantages. Non-uniform irradiance levels incident on the surface of photovoltaic (PV) modules within a PV power plant, mostly caused by passing clouds, reduce their performance. Therefore, proper management and operation of PV systems requires reliable knowledge of solar irradiance values at the application areas. Large-scale centralized PV power plants or distributed PV generators on wide geographical areas are examples of such systems and applications with precise and site-specific high resolution irradiance data requirement. However unavailability or incompatibility of data provided by measurement stations with the analysis requirements (unavailability of data for desired application areas or incompatibility of the resolution of data with the analysis purposes) and other limitations associated with the mentioned stations and equipment cause problems from PV analyses point of view.

The mentioned problems have motivated research studies to develop models for estimation of solar radiation and several models are proposed to estimate clear-sky radiation as well as radiation under cloudy sky to be utilized for PV analyses purposes. Irradiance data generated by irradiance estimation models forms the required input data for PV analyses purposes. Thus, an adequate irradiance model from PV research point of view should be able to consider interactions of sunlight with clouds and take into account cloud properties to provide reliable irradiance data for desired application areas. Such a model should be capable of generating high resolution spatial irradiance data incident on PV module surfaces within a PV array. Reliable analyses of PV system performance become possible once the required high resolution spatial irradiance data for the desired PV application areas is obtained by the mentioned irradiance models and/or measurement equipment.

Mathematical modeling of PV systems has been widely considered for investigation of system performance under variable environmental conditions. One-diode and two-diode mathematical models of a solar cell have been widely utilized for the mentioned purpose (Liu and Dougal, 2004; Villalva et al., 2009; Ishaque et al., 2011a, 2011b). These models generally estimate PV system characteristics utilizing datasheet parameters provided by PV manufacturers along with environmental parameters such as solar irradiance and temperature.

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Nomenclature

cc	cloud cover [%]	$\overline{G}_i$	average irradiance of the ith row [W/m^2]
LT	local time	G_{ij}	incident irradiance on the jth PV module of the ith row [W/m^2]
N_{PV}	number of PV modules in the array	$\overline{G}$	array's average irradiance [W/m^2]
N_{SW}	number of switching actions	ΔG	irradiance threshold [W/m^2]
I_{ph}	photo-current [A]	l	number of PV modules in a row
I_S	diode saturation current [A]	P_{NR}	array's non-reconfigured maximum power [W]
n	diode ideality factor	$P_{OPT.}$	array's maximum power under ideal conditions [W]
R_S	series resistance [Ohms]		
R_{SH}	shunt resistance [Ohms]		

Taking proper precautions and application of efficient strategies to mitigate the negative effects of non-uniform spatial irradiance profiles are significantly important for PV system planning and management. Utilization of bypass diodes or different PV array architectures are examples of such strategies (Silvestre et al., 2009; Carannante et al., 2009). Series-Parallel (SP), Bridge-Link (BL) and Total-Cross-Tied (TCT) are the most widely utilized array configurations while the TCT topology provides higher efficiency in reducing losses caused by non-uniform spatial irradiance profiles (Ramaprabha and Mathur, 2012; Kaushika and Gautam, 2003).

Dynamic reconfiguration of PV module interconnections within a PV array is another leading-edge research area. Velasco-Quesada et al. (2009) proposes an optimization algorithm based on irradiance equalization index, aiming for creation of series connected rows of parallel connected PV modules with average irradiances equivalent to the array's average irradiance. The algorithm examines all possible array configurations and selects the most proper configuration. The reconfiguration of PV modules is considered as a mixed integer quadratic programming problem in (Shams El-Dein et al., 2013) with capability of utilization with non-equal module number per row. Wilson et al. (2013) propose an iterative and hierarchical sorting algorithm based on irradiance equalization method in order to achieve near-optimal configuration considering number of switching actions, N_{SW}. Connection of an adaptive bank of modules to a fixed part of the PV array through a switching matrix, based on a model-based control algorithm is considered in (Nguyen and Lehman, 2008). Alahmad et al. (2012) propose a flexible switch array matrix topology for real-time power generation improvement.

The irradiance value incident on the surface of each individual PV module should be known for reliable analysis of the effects of non-uniform spatial irradiance profiles on PV power production. This paper utilizes a modeling technique which generates spatially dispersed irradiance profiles incident on PV module surfaces at the application sites. The model utilizes real sky images and accounts for light interaction properties of different cloud types to generate irradiance profiles based on the existing cloud patterns and their sunlight interaction properties. A simple reconfiguration algorithm which is based on irradiance equalization method is proposed to reduce losses caused by non-uniform spatial irradiance profiles on PV systems. The algorithm aims for providing near-optimal array reconfiguration in terms of irradiance equalization and N_{SW}. The contributions of this paper are mainly to the utilization of site-specific irradiance profiles based on existing cloud distributions for analyses of the effects of non-uniform spatial irradiance profiles and the dynamic and simple reconfiguration algorithm which offers no limits on the number of PV modules included within the array and shading profiles alongside with the significant improvements in power generation. This paper addresses the need to a simple dynamic reconfiguration algorithm to mitigate negative effects of non-uniform spatial irradiance profiles induced on the extent of PV plants, mainly caused by the existing clouds. The innovation of this work is the design of an algorithm capable of dynamic reconfiguration of the interconnections of PV modules within a PV plant according to the spatially dispersed irradiance profiles incident on the PV plant area at any instance. The algorithm, which operates based on irradiance equalization principle, provides near optimal PV array configurations in order to generate approximately the maximum possible power under non-uniform spatial irradiance profiles at any instance. The algorithm also considers reduction of number of switching actions in order to preserve the lifetime of switching devices. For this purpose, unnecessary switching actions which do not provide significant contribution to power generation are eliminated. In this way, yielding approximately maximum possible power generation alongside with minimum reconfiguration and switching numbers are ensured under non-uniform spatial irradiance profiles.

The remaining parts of the paper are organized as follows. The model utilized for generation of Spatially Dispersed Irradiance Profiles (SDIPs) for the application sites is briefly presented in Section 2. Section 3 provides a brief review on mathematical modeling of PV systems and different PV array architectures and presents the proposed PV array reconfiguration algorithm and its application through a dynamic switching matrix.

2. Model of spatially dispersed irradiance profile

Significant analysis of the effects of non-uniform spatial irradiance profiles on PV arrays requires high resolution spatial irradiance data incident on PV module surfaces. This study utilizes a modeling technique developed to generate Spatially Dispersed Irradiance Profiles (SDIPs) at the application sites based on existing clouds and their properties. The model deploys 2D latitude-longitude sky images serving as cloud coverage drivers and processes them to generate SDIPs. The utilized sky images are 720×576 RGB images taken by a commercial camera on per-minute time basis. Sky images are particularly selected to represent samples of different sky conditions (from partly cloudy sky conditions with different cloud coverages up to overcast sky). The criterion for selection has been representation of different cloudiness amounts and cloud distributions. The provided irradiance profiles are generated based on 4 independent samples of sky images. The model is explained here with its general lines while detailed information regarding the model can be found in our previous study. Fig. 1 briefly presents different steps of the model. The irradiance model considers different cloud types and their sunlight interaction characteristics (cloud transmittivity) to generate irradiance profiles incident on PV arrays. Cumulus cloud is utilized in this paper as a common cloud type that is also consistent with the utilized sky images. The ground coverage area of each irradiance profile depends on Cloud Base Height (CBH) values as defined by Chow et al. (2011). As the precise coordinates of the ground coverage area of irradiance profiles (e.g. in meters) may