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A novel Zig-Zag scheme for power enhancement of partially shaded solar arrays

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ABSTRACT

This paper proposes a novel Zig-Zag scheme of arrangement for the total cross tied interconnection of photovoltaic modules for reducing partial shading losses and thus enhancing power generation. The performance improvement over classical total-cross-tied connection has been validated by extensive simulation results. The novel scheme of arrangement is also compared with the optimal total cross tied configuration and results show that the new scheme of arrangement showed very similar operational characteristics. The rearrangement of modules is performed without varying the electrical connection of the modules in the array. Simulation results shows that the new scheme of rearrangement lessens the number of multiple local maxima in power–voltage (*P–V*) characteristics which further simplifies the Global Maximum Power Point (GMPP) tracking algorithm. The performance of the system is investigated for five different shading patterns.

1. Introduction

SOLAR power is achieving much importance due to fast declining cost of photovoltaic (PV) cells and enormous technological developments in the area of power electronics. PV generators convert the energy of solar radiation directly to electrical energy without any moving parts. The electric grids, commercial and domestic utilities have specific voltage levels. They are much higher than the maximum voltage of single silicon based PV cell. The PV cells are connected in series to form PV modules. The individual voltage level of a PV module is normally too low to be conveniently used in grid connected PV power generator. Hence the generators are built by connecting PV modules in series and parallel in order to acquire the appropriate voltage level and also to increase the nominal output power of the generator.

1.1. Present state of the art

Photo voltaic systems for power generation convey many challenges. The short circuit (SC) current of the PV cell varies due to several technical and environmental reasons. The major environmental reason for uneven SC current is the partial shading of the PV array due to dust and dirt on the panels, shadows imposed on the array due to passing clouds, nearby trees, buildings, etc. Recently there is an increasing trend to incorporate the PV arrays at the design level of a building itself. In those circumstances, it is a challenging task to avoid partial shading of array due to nearby buildings during the day at all seasons. This makes the study of partial shading of modules a key issue. In recent years, the impact of partial shading on the PV array performance has been extensively discussed.

1.2. Literature review

Research work in this field took shape after several instances on solar cell failure were reported due to unexpected shading sources. When the series connected cells do not operate under uniform conditions, the electrical characteristics of the cells are not similar and are exposed to mismatch losses (Lashway, 1988). Hot spot regions are developed in the shaded cells which result in the localized shading, lower power output and a hastening of the material degradation in the affected area. In 1979, damage due to hot spot heating was observed at test sites at Mead, Nebraska and Arlington, Texas (Forman and Themelis, 1980). To mitigate this phenomenon Green et al. (1984), Sheperd and Shigimura (1984) proposed to integrate bypass diodes into solar cells (Green et al., 1984). The power output of the shadowed solar cell arrays were substantially improved when each row of parallel cell strings (series blocks) is shunted by the bypass diode (Swaleh and

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Green, 1982). The prospective on the design of bypass diodes configuration integrated in a PV module and also on the study of PV generators working under partial shading conditions was carried out in Sheperd and Shigimura (1984). Experimental analysis on the impact of reverse biasing due to shading on amorphous silicon modules and crystalline silicon modules made by different manufacturers are evident in Molenbroek et al. (1991). Amorphous silicon modules were lesser prone to crystalline silicon modules. Also, for the crystalline and amorphous silicon PV modules investigated, failures due to hot spot heating are unlikely to occur when bypass diodes were employed. PV modules with bypass diodes do not generate any useful power when the diodes are ON. Further, these diodes produce surplus power loss due to their ON resistances (Silvestre et al., 2009). In Acciari et al. (2011), a novel circuit was suggested to avoid bypass diode ON resistance losses. But, this circuit does not recuperate the power that is lost due to bypassing of the modules.

PV modules that are connected in parallel can cause reverse currents under partial shading. These reverse currents lead the modules to absorb power rather than generating it, which reduces the generation and increases the thermal losses. Thus PV arrays are equipped with reverse current blocking diodes to inhibit reverse currents. The operation of these series reverse blocking diodes which are used to prevent current imbalance in series parallel circuits is detailed in Bishop (1988). The impact of reverse currents under different operating conditions on the Current–Voltage (*I–V*) characteristics is studied in Spertino and Akilimali (2009). The simulation results showed that the impact of the *I–V* mismatch is insignificant with normal tolerance and the inclusion of blocking diodes against reverse currents can be avoided with crystalline silicon technology.

Comprehensive research on partial shading progressed from 1995, after Volker Quaschning et al. projected huge loss in photovoltaic generators due to partial shading. They proposed an appropriate scheme for computing the irradiance of the solar cells of a shaded photovoltaic generator (Quaschning and Hanitsch, 1995). The influence of module shading on its performance was reported by the same authors Quaschning and Hanitsch (1996). The performance loss was found to be reduced by 70% when only 2% of the module area was shaded. The mismatch losses and the power losses due to tracking of local MPP instead of the global one for long string, parallel string and multi string configurations has been studied in Maki and Valkealahti (2012). Results showed that long series connection of modules and parallel connections of strings through a single inverter to the electrical grid should be curtailed to avoid losses under partial shading conditions.

The power loss due to partial shading is not proportional to the shaded area alone but depends on the shading pattern, array configuration and the position of shaded module in the array. Different array configurations have been proposed in literature to reduce the mismatch losses in the array. The modules were Series-Paralleled in which a branch circuit was divided into series blocks to reduce the effects of electrical mismatches (Boronat and Chouder, 2009; Gonzalez and Weaver, 1980; Ross, 1982). Similar interconnection schemes have been proposed and tested in Appelbaum et al. (1977) and Brandstetter, 1983. In (Kaushika et al., 1988), three suitable configurations schemes viz., Series-Parallel (SP), Total Cross Tied (TCT) and Bridge Linked (BL) are compared for their losses, maximum power, fill factor, reliability and energy yield due to mismatch loss caused by the partial shading and manufacturer's tolerances in cell characteristics. Study shows that changing the interconnection schemes of the modules from SP to TCT increases the power by more than 5% and the TCT configuration is considered as the best solution to lessen the mismatch losses under partially shaded conditions. An analysis based on probability theory indicates that introduction of cross ties (TCT or BL schemes) in the array almost doubles the life time of the array (Kaushika and Gautam, 2003). SP, TCT, BL, Simple Series (SS) and Honey Comb (HC) configurations have been compared in terms of maximum power and fill factor in Gautamand and Kaushika (2002). The TCT configuration has maximum power compared to other configurations under the same conditions of partial shading. The investigation shows that there is no additional cost for TCT-connected modules than SP-connected modules in large solar parks.

The solar PV system can also be extensively used in many small scale consumer applications, such as PV vests for cell phones and music players. In (Silvestre et al., 2009), a configuration is proposed which consists of an array of parallel-connected PV cells, a low-input-voltage step-up power converter, and a simple wide bandwidth MPP tracker. Parallel-configured PV systems are compared to traditional series-configured PV systems through both computer simulations and hardware experiments. Study shows that, under complex irradiance conditions, the power generated by the new configuration is approximately twice that of the traditional configuration.

One of the thrust areas of research recently in the field of partial shading is the implementation of modified classical MPPT techniques. When the bypass diodes conduct during non-uniform condition, *P–V* curve of the solar array shows multiple maxima. Thus the extraction of maximum power from the PV array becomes complex since there exist several local maximum power point (MPP) at low voltages and at higher voltages. Hence classical MPPT techniques which track the unique singular MPP in array characteristics under uniform irradiance conditions cannot be implemented. Under partial shading, the MPPT will identify a local optimal point as the global maximum point, thus leading to power losses. Approaches to track the global maximum power point (GMPP) have been demonstrated as in Wang and Hsu (2011), Patel and Agarwal (2008a,b), Esram and Chapman (2007), Safari and Mekhilef (2011), but they tend to be complicated and many of them are unable to track the GMPP under changing illumination conditions. The development of different MPPT techniques to determine GMPP involving modified heuristic techniques is another recent area of research work. In Huynh et al. (2013), a new GMPP tracking strategy for PV array under partial shading using a dynamic particle swarm optimisation (PSO) algorithm was proposed. A deterministic PSO to improve the maximum power point tracking capability for PV system to address the rapid movement of the passing cloud is evident in Ishaque and Salam (2013). The analyses carried out in Ishaque et al. (2012) using synthetic current–voltage data set showed that the proposed penalty based differential evolution (P-DE) outperforms other evolutionary algorithm methods, namely the simulated annealing (SA), genetic algorithm (GA), and PSO. P-DE consistently converges to the global optimum values very rapidly. A method using Lambert W-function facilitating a direct tie between current and voltage of modules which significantly reduced calculation time has been proposed in Picault et al. (2010) to forecast the maximum power production from the existing PV systems. In Batzelis et al. (2013), an explicit PV string model using the Lambert *W* function was introduced, showed the accuracy provided by the one-diode model with faster and more robust execution, intended to be used for energy yield calculations and PV system analysis and optimization. But the model is unable to track the GMPP under changing illumination conditions. A new design method for distributed maximum power point tracking (DMPPT) synchronous boost converter is proposed in Adinolfi et al. (2015). Method is centered on non-dominated genetic algorithm with the purpose to obtain the finest synchronous rectification (SR) boost topology. A new method to track the GMPP under partial shading conditions using Radial Movement Optimization Technique (RMO) was adopted in Seyedmahmoudian