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Optimized Reconfigurable PV array based Photovoltaic water-pumping system

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ABSTRACT

This paper proposes a new strategy to improve the performance of a four-module Reconfigurable PV array (RPV) based water-pumping system. The four-module PV array undergoes a change in the configuration based on the irradiance received by the PV array, the pumping-head and the Partial Shade Condition (PSC). The reconfigured PV array operates the pump under low irradiance conditions and produces greater output power. This paper proposes three different switch-networks each with a reduced number of switches compared to the previously reported one. In addition, the proposed switch-networks report less operational losses. This paper proposes a simple algorithm and control circuit for smooth and reliable operation of RPV pumping system. A 40 W_P four module PV array based pumping tests are conducted. Results have validated the proposed strategy.

1. Introduction

For drinking, agriculture, dairy farming and other economic activities purposes, the rural people have installed many solar PV powered pumping systems to fetch water from the underground, well and river resources (Talbi et al., 2018; El-Khatib et al., 2017; Yadav et al., 2015; Salameh et al., 1990; Salameh and Dagher, 1990; U.M. o. P. Central Electricity Authority, 2001; S. Foundation, 2014; Manjunath et al., 2017; Deshkar et al., 2015; Dhanalakshmi and Rajasekar, 2018). Under ideal conditions, a PV pumping system (PVPS) should start comfortably at low irradiance conditions and function normally at all time-of-the-day. In reality, it fails to start at low irradiance conditions. In addition, it delivers rated output power during peak irradiance conditions only.

To improve the Photovoltaic pumping performance, many novel schemes have been reported in the literature. Originally, the majority of them had focused on either reducing the number of stages of power conversion or, improving the maximum power point tracking (MPPT) controller performance (Manjunath et al., 2018). In Sashidhar and Fernandes (2017) and Kumar and Singh (2016), a two-stage PVPS is proposed to exercise a wide range of control over the functioning of the scheme. This approach produces greater pumping output at all operating conditions. However, incurring high operational losses and increased cost of investment are the drawbacks. In Antonello et al. (2017) and An and Lu (2015), a single-stage pumping scheme is reported. Unlike a two-stage, it exerts an efficient control and reports high efficiency.

Contrary to the approach in Sashidhar and Fernandes (2017), Kumar and Singh (2016), Antonello et al. (2017) and An and Lu (2015), few research works have focused on improving the per-day pumping output. In Maranho et al. (2016), fuzzy logic controller based variable-speed drive (VSD) PV pumping scheme is reported. The dc link voltage and the pumping-motor frequency both are controlled to make the PVPS available even under the low PV output conditions, which is the main advantage. However, the high cost of investment is a drawback.

A rural consumer may select and install one of the above PVPS (Sashidhar and Fernandes, 2017; Kumar and Singh, 2016; Antonello et al., 2017; An and Lu, 2015; Maranho et al., 2016) if high cost of investment is not a problem. However, a minimum duration for which the PVPS operates without developing any circuit related issues is not known. In addition, the electrolytic capacitors present in the PVPS circuit often fail (Agarwal et al., 2016). The rural PVPS owner may find it difficult to rectify the problem. In addition, absence of proper transportation systems may cause them permanently non-functional.

A novel Reconfigurable PV array (RPVA) based water pumping scheme has been reported (Salameh and Dagher, 1990; Salameh et al., 1990). The four-module PV array is reconfigured to improve the pumping performance. The four-module connections are altered dynamically through a switch-network to connect the PV array in one of three configurations as shown in Fig. 1 as and when desired. As a result of this strategy, the PV pumping scheme starts at low irradiance conditions and improves per-day water-pumping output. It is a simple and highly potential technique to improve per-day pumping output. In addition, the absence of energy storing elements makes the RPVA a highly reliable technique to the rural area applications.

Compared to the multi-stage and other well-known PVPS techniques

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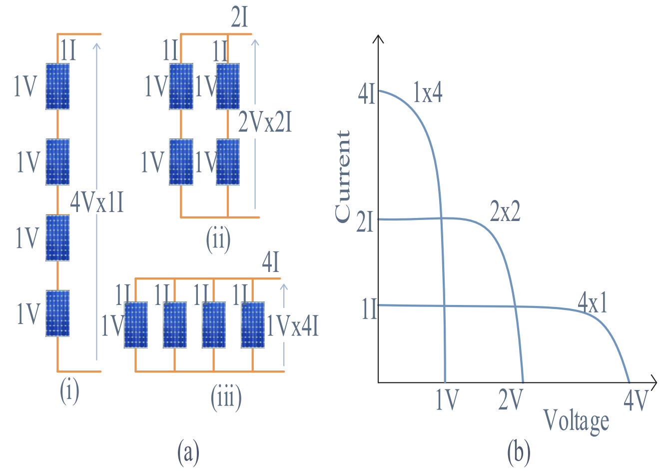

Fig. 1. A four module RPVA connects the modules in any of three series–parallel configurations: 4×1, 2×2 and 1×4.

(Sashidhar and Fernandes, 2017; Kumar and Singh, 2016; Antonello et al., 2017; An and Lu, 2015; Maranho et al., 2016), proposed RPVA based PVPS does not require a power converter and ensures a high percentage of power conversion (Spagnuolo et al., 2015). However, unlike (Sashidhar and Fernandes, 2017; Kumar and Singh, 2016; Antonello et al., 2017; An and Lu, 2015), an RPVA scheme may not operate the PV array at Maximum Power Point (MPP) for all the irradiance and pumping-head conditions (Spagnuolo et al., 2015). Yet, the increased per-day pumping-output may compensate and provide compatible benefits compared to the MPPT techniques.

In recent years, many grid-tied RPVA systems have been installed across the European countries (Viola et al., 2016). Even more, a specialized and patented version of RPVA product called 'Endana' is available in the market (Bitron, 2015). Despite the developments and good progress in reconfiguration PV systems, the proposed RPVA based water pumping scheme (Salameh and Dagher, 1990) could not popularize. Implementation of a highly complex switch-network may be a reason for it. The switch-network is developed through the intelligent connection of nine IGBT switches. The presence of nine switches and a number of energy storing elements etc., all made it a lossy and disadvantage switch-network. In addition, the poor algorithm is sensitive to changes in input insolation and not to the output pumping-head or the Partial Shade Condition (PSC) (Salameh and Dagher, 1990).

Reducing the complexity of RPVA, many new switch-networks are reported (Zhao et al., 2012; Manjunath et al., 2015; Nguyen and Lehman, 2008; Spagnuolo et al., 2015; Nakagomi et al., 2010; Storey et al., 2013; Karakose and Baygin, 2014; Velasco Quesada et al., 2009; Lin et al., 2015). In (Zhao et al., 2012), a 'single pole single throw' (SPST) relay based switch-network is introduced. Compared to a semiconductor, the SPST is a 'mechanical' switch and has negligible conduction resistance. Hence, it made the switch-network highly efficient. However, requiring nine SPST switches is a principle drawback. In Manjunath et al. (2015) a multichannel 'single pole double throw' (SPDT) switch-network (Salameh and Dagher, 1990) is presented. It reduces the switch-count nine (Zhao et al., 2012; Salameh and Dagher, 1990) to eight. However, switch-count of eight is still a high number. In Matam and Reddy (2018), switch-network of double pole double throw (DPDT) relays for reconfiguration of a six-module PV array is proposed. However, this network is not applicable to the reconfiguration of a four module PV array.

In comparison to a semiconductor switch, a relay operates slowly (E. Tutorials, 2017). However, in case of RPVA systems, fast reconfiguration of PV array or switching of the PV modules is not a priority. From this point of view, switch-networks constructed from relays are efficient and reliable (Spagnuolo et al., 2015). In addition to above, galvanic separation present between the power-channel(s) and its control-coil is a good inherent feature of a relay (Spagnuolo et al., 2015). It avoids the need for separate isolation circuitry arrangement. However, when connected to an inductive (motor) load, force closing and opening of mechanical switches can cause arcing phenomenon across the terminals. Connecting a snubber circuit across the relay switch or a free-wheeling diode across the motor output terminals can suppress the arcs and minimizes the damage to relay switches (E. Tutorials, 2017).

The main objective of this paper is to improve the performance of RPVA based water pumping system. Some of the main contributions of this paper are summarized below:

1. Three different switch-networks with different switch-count are proposed. Each of the switch-network has a less switch-count compared to previous switch-networks (Salameh and Dagher, 1990; Manjunath et al., 2015).
2. A simple algorithm to sense and control the RPVA is proposed. It can be used to sense and control any of the switch-networks.
3. Small-scale outdoor tests under various insolation, pumping-head and partial shading conditions (PSC) are conducted. Results have validated the superior performance of the proposed RPVA under various operating conditions.

Rest of this paper is presented in the following order: Reconfigurable PV array and pumping-motor problem formulation in Section 2, schematic of proposed RPVA based PVPS in Section 3, proposed switch-networks in Section 4, description of control algorithm and logic circuit in Section 5, experimental setup description in Section 6, results discussion in Section 7 and conclusions in Section 8.

2. RPVA and Pumping-motor equations

2.1. PV cell, module and array equations

A Photovoltaic (PV) cell is the smallest component of Photovoltaic system that generates electricity. A PV array is constructed by connecting a number of cells in series and parallel. The PV array voltage equation is given by Kolhe et al. (2004)

$$V_{ary} = -I_{ary} R_{se} \frac{N_{aryse}}{N_{arypa}} + N_{aryse} F \frac{K_{bz} T}{q} ln\left(1 + \frac{N_{arypa} I_{ph} - I_{ary}}{N_{arypa} I_0}\right) \tag{1}$$

where N_{aryse} and N_{arypa} are number of cells in series and parallel, V_{ary} and I_{ary} are array voltage (V) and current (A), F is ideality factor ($1 \le F \le 2$), I_{ph} is photo generated current (A), I_0 is diode reverse saturation current (A), R_{se} is series resistance of the cell (Ω), K_{bz} is Boltzman's constant, T is the PV cell temperature (K), and q is an electron charge (ev). In above (1), substituting thermal voltage of the cell V_T $(=\frac{K_{bz}T}{q})$, $N_{aryse} = 1$, $N_{arypa} = 1$ gives the PV cell equation as given below

$$V_{cel} = F\, V_T\, ln\left(\frac{I_{ph} - I_{cel} + I_0}{I_0}\right) - I_{cel} R_{se} \tag{2}$$

where V_{cel} is cell voltage, I_{cel} is cell current. The above simplified Eq. (2) is obtained after neglecting the PV cell shunt resistance R_{sh}. A PV module is manufactured by connecting N_s number of cells in series. After making relevant changes to the cell Eq. (2), the PV module equation is given by

$$V_{mod} = N_s F\, V_T\, ln\left(\frac{I_{ph} - I_{mod} + I_0}{I_0}\right) - N_s I_{mod} R_{se} \tag{3}$$

where V_{mod} is module voltage, I_{mod} is module current. Further, a PV array is constructed by connecting 'm' numbers of PV modules in series across a string, 'n' numbers of series strings in parallel. Modifying the module Eq. (3) gives the PV array equation as given below

$$V_{ary} = m N_s F\, V_T\, ln\left(\frac{n I_{ph} - I_{ary} + nI_0}{nI_0}\right) - \frac{m N_s I_{ary} R_{se}}{n} \tag{4}$$

Above (4) is used to develop the array voltage vs. current (V-I)