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Switched-capacitor converter for PV modules under partial shading and mismatch conditions

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ABSTRACT

Partial shading and mismatch among the Photovoltaic (PV) modules is an important issue, which decreases the harvested power from the PV modules, and causes an efficiency problem for renewable energy systems. Several power electronics topologies that allow charge redistribution between the PV modules, have been proposed to balance PV modules which are connected in series. Differential Power Processing (DPP) is a technique which improves the overall efficiency of the power balance system by processing only a fraction of the module power. In this study, the power loss analysis of the switched-capacitor (SC) converter, which is configured in ladder architecture with the PV sub-modules for power balancing purpose, is derived and verified by simulation and experimental works. The proposed loss model predicts the percentage of power loss of the SC converter working under arbitrary partial shading conditions. Switched-Capacitor converter prototype was built and tested using a 140 W photovoltaic module. It is found that for 0–25% overall partial shading the overall efficiency remains above 98%. The experimentally obtained loss is in reasonable agreement with its theoretical counterpart.

1. Introduction

Partial shading in a PV string results in power-voltage characteristics which contain multiple local maximums, and this results in decreased power generation capability due to bypassed power (Chaieb and Sakly, 2018). The conventional hill-climbing based maximum power point tracking (MPPT) algorithms may converge to one of these local maximums and the amount of power that can be harvested from PV modules may decrease. This is an undesirable situation for energy harvesting systems. Several methods have been reported to handle these issues (Ahmad et al., 2017; Balasankar et al., 2017; Dileep and Singh, 2017; Zaki Diab and Rezk, 2017). The global maximum of a non-convex output power curve under partial shading is less than the sum of the peak powers of individual sub-modules and some amount of power can be recovered by using proper switch-mode power converter systems. These power electronics solutions are handled with the increased granularity from string level to sub-module level to improve power harvesting capability (Forcan et al., 2016). Cell-level MPPT can be thought as future smart PV modules, due to their high production costs (Orabi et al., 2015). For module level MPPT in shaded condition, the potential energy gain increases by 3–16% (MacAlpine et al., 2013).

Micro inverters bring a solution for module level MPPT and for direct AC power injection to the grid from one individual module (Petreus et al., 2013). This solution comes at additional cost due to the higher number of discrete semiconductor components. The DC-DC optimizers at the module level are proposed to solve the partial shading issue. To increase the MPPT granularity, DC-DC converter based solutions have been used at the sub-module level (Pilawa-Podgurski and Perreault, 2012). A sub-module is composed of a group of series connected cells in a single module which is in parallel with a one bypass diode. These converters can be grouped in full power processing approaches and they have several disadvantages such as limited efficiency and high cost. The disadvantages of the full power processors are mitigated by using the converters employing Differential Power Processing (DPP) ability, where common power of the string flows through the conventional string and differential power among the adjacent PV modules is processed through the converters and bypassed around the shaded PV modules. This differential processing method brings some advantages such as increased system level efficiency. Some of these DPP converters like switched-capacitor (SC) converter with the fixed conversion ratio forces the sub-modules to have equal voltages allowing the ‘near’ MPPT. Although some other topologies similar to the switched-inductor with the variable conversion ratio allow sub-modules to operate on ‘true’ MPP for each sub-module, but require more complicated

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Nomenclature

f_{sw}	switching frequency of the SC converter
C	capacitance value for balancer capacitors
SSL	slow switching limit
FSL	fast switching limit
ESR	capacitor's equivalent series resistance
q	charge flow
x	elements: c for capacitors, s for switches, ph for photo-current source, PV for photovoltaic module
i	index number for elements
φ	phase defining the switch positions
k	insolation level for PV modules
$(n+1)/2$	number of PV elements
α	charge multiplier
R_L	load resistance of PV string
R_{SSL}, R_{FSL}	SSL output impedance and FSL output impedance respectively
V_{MP}, I_{MP}	maximum power point voltage V_{MP} and current I_{MP} respectively
R_{DS_ON}	switch-on resistance
IL	insertion loss
STC	standard test conditions for PV modules

system-level coordination. The process of making MPPT with the increased granularity in a PV system is called as distributed MPPT (DMPPT) (Jeon et al., 2017).

Buck-boost converter (Qin et al., 2013a), resonant SC (ReSC) converter (Stauth et al., 2013), and fly-back converter (Chu et al., 2017; Olalla et al., 2014) are the most common topologies that are employed as DPP in a module integrated converter. These converters can be connected in shunt around the PV modules connected in series and can be evaluated as having well-suited modularity for the string sizes of the state-of-the-art PV system installations for residential as well as commercial or utility-scale application.

In this investigation the effect of partial shading on power-voltage characteristic is modeled by varying the photo-current generated by each series connected sub-module, and the effect of temperature is excluded since temperature mainly affects the voltage of PV element and has less effect on the current (Gokdag and Akbaba, 2014).

In this study, a power loss analysis for the SC converter employed as a power balancer in a PV string operating under partial shading is derived and verified by simulation and experimental works. In this analysis using the general principles of switched capacitor theory, power transfer between the shaded and unshaded PV sub-modules and the loss analysis are generalized for arbitrary number of PV modules in a string. This is the main contribution of this investigation as compared to the published literature (Blumenfeld et al., 2014; Chang et al., 2014; Stauth et al., 2012) in which switched-capacitor topologies are adopted as a solution to the partial shading problem but none of them proposed a power loss model which predicts the loss amount for an arbitrary shading. From the loss model proposed in this investigation the amount of power loss due to the operation of SC converter for an arbitrary shading pattern can be calculated easily without involving long-lasting simulation time. An SC converter prototype is constructed and tested on a PV module of 140 W. When using SC converter, for the case of 0–25% overall partial shading, the overall efficiency remains above 98%. The experimentally obtained loss results are in reasonable agreement with that of theoretical results. The simulation and experimental study also show that the SC converter can recover most of the power which would be bypassed in the absence of SC converter and hence it increases the harvested power.

The paper is organized as follows: Section 2 explains the operating principle of the SC converters and presents the derivation of power loss model for a randomly sized string working under arbitrary shading condition. Section 3 presents the simulation results and discusses converter operation under certain conditions. Section 4 introduces the prototype specifications and presents the experimental results. Also a comparison of the analytical and experimental results is given in this section.

2. Loss analysis of switched capacitor converter

The SC converter configured in ladder architecture is connected in parallel to the sub-modules to obtain a balanced series string as shown in Fig. 1. When the sub-modules are exposed to uniform irradiation and they have perfectly matching characteristics, there is no charge redistribution among these sub-modules which results in no loss. When partial shading occurs, the SC converter transfers differential charge among the adjacent sub-modules according to partial shading ratio.

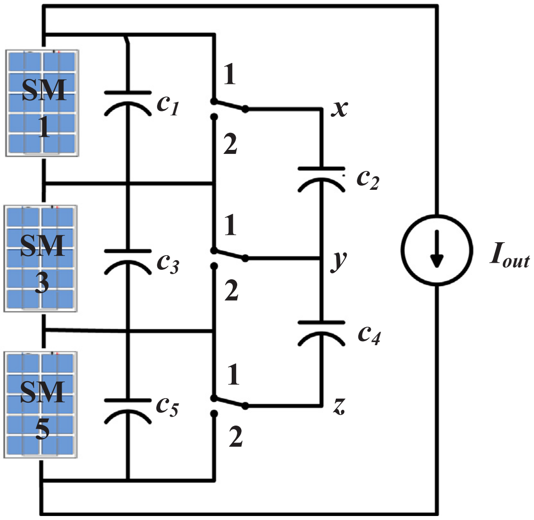

Fig. 1. String of PV sub-modules with SC converter.

During the charge transition between the input (sub-modules) and output of the power converter, the capacitors are charged and discharged periodically. This causes a voltage drop across the converter, which is an undesirable phenomenon. Since this voltage drop is proportional to the output current it can be represented as an output impedance, which can cause a decrease in the maximum efficiency that power converter can reach. Two asymptotic limits are defined for the output impedance of the SC converter, one for the Slow-Switching Limit (SSL) and another one for the Fast-Switching Limit (FSL), as related to switching frequency. The SSL is a metric that describes how fast the charges are transferred among the capacitors. It is inversely proportional to the switching frequency f_{sw} and capacitance value C. For SSL impedance calculation, the switches and all other conductive interconnects are assumed to be ideal. It is also assumed that in the SSL, the currents flowing between the input and output ports and through the capacitors are impulsive, which can be modeled as charge transfers. Further to this the voltage waveforms across the capacitors can be assumed having square wave shape. When the converter operates with a high-enough switching frequency, the FSL occurs. In the FSL, the resistance of the circuit path between capacitors which is composed of the switch on-state resistance, the capacitor's equivalent series resistance (ESR) and the interconnects becomes the major source of the output resistance. Then the FSL impedance is proportional to this resistance. During FSL operation, the voltages of the capacitors are constant, and the current between capacitors are in square wave shape (Seeman and Sanders, 2006).