Renewable and Sustainable Energy Reviews 76 (2017) 516–528

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Review and qualitative analysis of submodule-level distributed power electronic solutions in PV power systems

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ARTICLE INFO

Keywords:
DC-DC power conversion
Energy harvesting
Photovoltaic power systems

ABSTRACT

Conventional photovoltaic (PV) systems make use of series-connection of PV panels, arranged into strings, in order to provide a voltage-stack at the input of grid-tied inverters. The string solution forces all PV modules to share the same current which results in power loss in presence of any mismatching condition. The emergence of Distributed Maximum Power Point Tracking (DMPPT) PV systems, which increase the level of MPPT fineness, provided an effective solution to mitigate the mismatch impact on energy harvest. The earlier DMPPT systems consisted of module-level power electronic solutions such as microinverter, DC Power Optimizer (DCPO), and Differential Power Processor (DPP). The recent studies increase the level of MPPT granularity and focus further to the submodule-level in order to alleviate the intra-panel mismatch problem and maximize solar energy harvest. The research on the topic resulted in a group of DMPPT systems that are classified as the submodule integrated converters (subMICs), submodule-level DPP (subDPP) and submodule-level isolated-port DPP (subIPDPP). This study focuses on the various implementations of these architectures and provides an in-depth analysis regarding to their advantages and limitations.

1. Introduction

Conventionally, PV panels are connected in series to form a string to achieve high stacked DC voltage, and then the strings are connected in parallel to create an array. Such configurations are categorized as centralized PV systems since the whole array power is processed at one point for grid integration [1–6]. These systems generally demonstrate very high power conversion efficiency but have been proved to be ineffective for solar energy harvesting under various non-ideal conditions [7]. The loss is mainly caused by the unbalanced generation among PV modules, as reported in [8–10], which is commonly caused by partial shading, non-uniform panel degradation, dirt accumulation, aging, thermal gradients, or manufacturing imperfections etc. To overcome the mismatch problem, distributed maximum power point tracking (DMPPT) solutions have been proposed at different levels of granularity. The hierarchy of DMPPT PV architectures including four levels of granularity – string-level, module-level, submodule-level and cell-level – is demonstrated in Fig. 1. The acronyms of SL, SC and ReSC refer to switched inductor, switched capacitor and resonant switched capacitor converter topologies, respectively, which will be explained and analyzed in the later sections.

The distributed structure at string-level is proposed in [11–14] which employs maximum power point trackers to each string. This structure eliminates the power loss due to mismatch among strings, however, significant loss can result from the mismatch within the strings. The mismatch among PV modules not only affects maximum power point tracking (MPPT) but also causes hotspots. To avoid hotspot occurrence, bypass diodes are utilized and connected in parallel with the PV modules or cell-strings within PV modules [15]. Nevertheless, the power loss caused by bypassed PV cell-strings is high because the whole PV cell-string needs to be bypassed even if only small part is shadowed [16,17]. The introduction of bypass diodes causes an additional problem of multiple maxima in power-voltage (*p*-V) curve, which makes the global MPPT a difficult task and does not always eliminate the hotspot phenomenon [18]. Therefore, to account for the mismatch problem within a string, module-level DMPPT solutions are proposed which implement MPPT converters with individual PV panels. These architectures include module integrated parallel converters (MIPC) [19–21], microinverter [22–31], module integrated series converters (MISC) or DC power optimizers (DCPO) [32–37], and generation control circuit (GCC) or Differential Power Processors (DPP) [38–40]. The common DC-DC topologies for MISC are buck, boost and buck-boost while MIPC generally require step-up conversion; therefore, utilize boost, coupled-inductor or flyback topol-

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http://dx.doi.org/10.1016/j.rser.2017.03.073
Received 16 June 2016; Received in revised form 15 February 2017; Accepted 16 March 2017
1364-0321/

Nomenclature

DCPO	DC Power Optimizers
DMPPT	Distributed Maximum Power Point Tracking
DPP	Differential Power Processors
Dx	Converter duty cycle and 'x' signifies the index
FPP	Full Power Processor
GCC	Generation Control Circuit
I_{MPP}	MPP current of a PV panel
I_{MPP_sub}	MPP current of a PV submodule
MPPT	Maximum Power Point Tracking
η_{GMPPT}	Global MPPT efficiency
η_{inv}	DC-AC inverter efficiency
η_{LMPPT}	Local MPPT efficiency
N_s	Number of submodules in a system
η_{subDPP}	System efficiency of subDPP architecture
$\eta_{subIPDPP}$	System efficiency of subIPDPP architecture
η_{subMIC}	System efficiency of subMIC architecture
PV	Photovoltaic
Po	Converter processing power with the converter index of 'x'
Px	Total string power output with the implemented subDPPs.
ReSC	Resonant Switched Capacitor
SC	Switched Capacitor
SL	Switched Inductor
SM	Submodule
subDPP	submodule-level Differential Power Processor
subIPDPP	submodule-level Isolated-port Differential Power Processing
subMIC	submodule Integrated Converter
v^*_{pv}	Reference PV submodule voltage
V_{DC}	Voltage at the DC side of the inverter
V_{GRID}	Grid voltage
V_{MPP}	MPP voltage of a PV panel
V_{MPP_sub}	MPP voltage of a PV submodule
V_{OC}	Open circuit voltage of one PV panel
α	Factor signifying processed power in subDPPs
β	Factor signifying processed power in subIPDPPs

ogy for MPPT operation. The microinverter concept has been proven with DC-AC topologies of different types including flyback, push-pull and three-port converters. The module-level DPP architecture has been demonstrated with SL, ReSC and gyrator converter topologies, which will be introduced in the following sections.

The panel-level PV harvesting has demonstrated encouraging results, which served as a first-step towards the fine granularity of MPPT [38]. The panel-level FPP architecture of DCPO offers multiple advantages ranging from energy savings to greater flexibility in overall system design [32–35]. The DCPO system allows PV modules to be decoupled from the string thus facilitating independent MPPT operation. Since each PV panel is equipped with a dedicated converter and MPPT controller, a panel-level power monitoring system can be implemented without adding too much complexity. Thus, with the real-time information of each PV panel, the diagnosis and maintenance of the whole system becomes available.

Microinverters, DCPO, MIPC and DPP are modular architectures which only eradicate the inter-panel mismatch losses. However, in real-world PV systems, mismatch scenarios rarely result in shading of the complete PV panel. Because of the panel-level connection, these structures are unable to mitigate the intra-panel mismatch loss [41]. Therefore, to eliminate intra-panel mismatch loss the fine-granularity MPPT at submodule-level is explored. The submodule is a section of a PV module, which consists of 15–24 cells in series connection and is connected in parallel with one bypass diode. Silicon-based PV modules are commonly composed of 60 or 72 solar cells in series connection, which are sectioned by three or four submodules.

The submodule-level DMPPT solutions can be categorized as full power processor (FPP) and differential power processor (DPP) architectures, as shown in Fig. 1. The distinctive interconnection of submodules with DC-DC converters for distributed submodule-level architectures is demonstrated in Fig. 2. In the existing literature the submodule-level FPP is commonly referred as submodule-level power optimizers or submodule Integrated Converters (subMICs) [41–50], as illustrated in and Fig. 2(a). The submodule-level differential power processors are categorized into two types which are different in connection: PV-PV and PV-bus. The PV-PV architecture, shown in Fig. 2(b), is termed as PV-PV submodule-level Differential Power

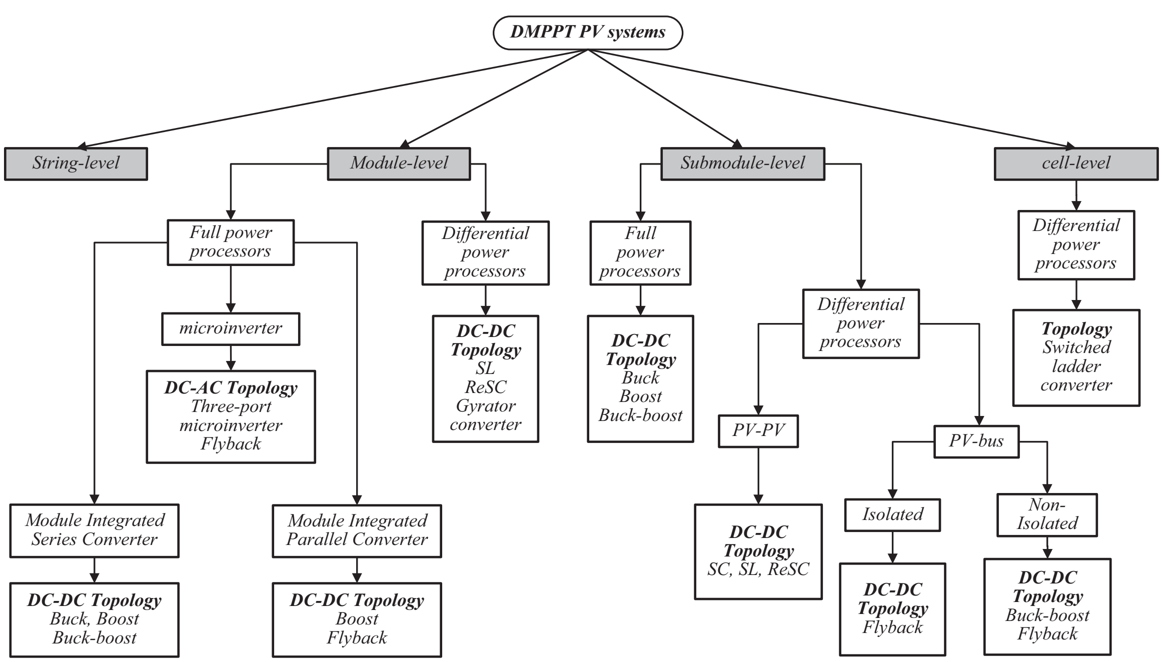

Fig. 1. Hierarchical diagram of DMPPT PV architectures showing different levels of granularity.