Photovoltaic Module and Submodule Level Power Electronics and Control

GRID-CONNECTED photovoltaic (PV) energy systems have experienced an explosive growth over the last decade, with a cumulative installed capacity surpassing the 400 GW milestone as of 2017. Among PV system configurations, distributed module-level converter architectures can lead to a higher energy yield by mitigating partial shading, persistent shading (soiling, snow, bird droppings, and fallen leaves), mismatch, and aging, through a higher maximum power point tracking (MPPT) efficiency. Also, distributed electronics might be the key for implementing diagnostic and prognostic actions at a module level. Among these configurations, microinverters (also known as ac-module inverter), which connect a single PV module to the grid, and PV power optimizers, which are dc–dc converters performing the MPPT function at a module level, have attracted the academic and industrial interest in the last decade. So much so, that both microinverters and dc–dc power optimizers are commercialized by tens of companies around the world, with a great variety of circuit topologies, which comprise combinations of one or more power stages, interleaved converters, resonant converters, topologies with and without isolation, etc.

Although compared to central, string, and multistring inverter configurations, module-level PV configurations ensure a higher level of harvested energy; they often exhibit a lower power conversion efficiency due to the additional power converter stages and due to the high-voltage step-up ratios required for the grid connection. Therefore, the design of more efficient converter stages has been and continues to be one of the main drivers of the R&D community. In addition, power density plays a fundamental role, particularly for this PV application, since the power converter is usually installed behind the PV module, in many cases between the module and the roof. More recently, reliability and fault tolerant operation have become increasingly relevant since commercial microinverters and dc–dc power optimizers aim to match, or at least shorten, the lifetime difference between the power converter and the PV module (the current warranty is typically 25 years, depending on the manufacturer). The input voltage range is a key aspect of module-level power processing systems. This is due to the operation of the bypass diodes of the substrings during partial shading, which when conducting, can produce a significant voltage drop across the PV module. This increases the voltage step-up ratio requirements up to a point in which it is not feasible for several converter topologies. The motivation for this special section has been to gather the latest achievements on PV-module-level power electronics research to sample the current state of the art and see where it is heading.

This special section received a total of 27 papers, nine of which were accepted for publication [items 1)–9) in the Appendix]. The work in [items 1)–5) in the Appendix] deals with the topic of high step-up voltage requirements and efficiency for PV-module-level power converters. In [item 1) in the Appendix], a hybrid high step-up dc–dc converter is proposed by merging a standard boost converter with a coupled inductor and different switched-capacitor techniques, achieving a high voltage gain and efficiency, whereas lowering the voltage and current stresses of the components. In [item 2) in the Appendix], another hybrid approach is presented, this time based on a synchronous quasi-*Z*-source series resonant dc–dc converter with an integrated series resonant tank. The converter operates with a variable dc-link voltage that optimizes efficiency for a wide range of input voltages, for which it has been given the concept name of Optiverter. The work in [item 3) in the Appendix] tackles the same issue from a different perspective by using a Cuk converter integrated with a switched-inductor technique. As a result, a high static gain with a reduced switch voltage is obtained in a nonisolated structure, resulting in less volume and losses. Another transformerless, wide input range microinverter is presented in [item 4) in the Appendix]. The converter is composed by a three-phase extended-duty-ratio boost as dc–dc stage and a doubly grounded voltage swing inverter as dc–ac stage. It is a hybrid of an interleaved boost and switched capacitor concept capable of achieving high gain while simultaneously maintaining low voltage and current stresses, whereas the common grounding feature eliminates the capacitive-coupled common-mode ground currents. In [item 5) in the Appendix], an optimized phase-shifted control strategy for a bridge modular switched capacitor converter used for energy storage in PV systems is proposed. With this control, the converter is capable of a wide regulation margin at step-down or step-up modes, capable of bidirectional power flow. In addition, the converter can operate in some regions with zero voltage switching, achieving high efficiency.

With regards to converter reliability, fault diagnostics, and fault tolerant operation, three contributions are included in this special section [items 6)–8) in the Appendix]. The work in [item 6) in the Appendix] deals with the wear-out failure of an impedance-source PV microinverter. The analysis is performed based on system-level electrothermal modeling combined with finite-element simulations and experimental measurements. The study reveals that the dc-link electrolytic capacitor is the component affecting long-term reliability. Changes in the dc-link

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capacitor and in the control, including variable dc-link voltage operation, are proposed to achieve reliability improvements. In relation to fault diagnostics, the work in [item 7) in the Appendix] introduces fault detection at module level based on monitored data by the microinverter and day-ahead power forecasting. In addition, a suitable procedure has been proposed for real-time monitoring of fault conditions by comparing neighbor PV modules. Results presented in this paper showed that this approach is able to identify critical failures of PV modules, avoiding systematic errors like aging or regular shadows. On the other hand, in [item 8) in the Appendix] proposes a redundant synchronous switch in a two-stage buck/buck–boost converter to enable fault-tolerant operation during open-switch faults. Due to the way the circuit reconfigures during fault, postfault operation still retains full power capabilities of the converter. An optimized fault-tolerant control, suitable in both healthy and postfault operations, is also presented in the paper.

Finally, the work in [item 9) in the Appendix] deals with the practical implementation of communications between dc–dc power optimizers. This is achieved by the authors, by embedding the power line communication data modulated directly into the control loop of the power converter, and then transmitted through the series-connected dc power line to other power optimizer. One of the advantages is that only few additional components are required for the implementation of the method. The performance, quality, and limitations of the communications are also discussed in the paper and validated experimentally.

We hope this special section serves as a reference and update for academics, researchers, and practicing engineers in order to inspire new research and developments that can pave the way for the next generation of microinverters and dc–dc power optimizers.

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APPENDIX
RELATED WORK

1) A. M. S. S. Andrade, L. Schuch, and M. L. da Silva Martins, “Analysis and design of high-efficiency hybrid high step-up dc-dc converter for distributed PV generation systems,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3860–3868, May 2019.
2) D. Vinnikov, A. Chub, E. Liivik, R. Kosenko, and O. Korkh, “Solar optiverter—A novel hybrid approach to the photovoltaic module level power electronics,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3869–3880, May 2019.
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9) Y. Zhu, J. Wu, R. Wang, Z. Lin, and X. He, “Embedding power line communication in photovoltaic optimizer by modulating data in power control loop,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3948–3958, May 2019.

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