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Efficient and Reliable Power Conversion Techniques for Distributed Photovoltaic Applications

Abstract

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The global effort towards more sustainable energy production systems is fostering the widespread diffusion of both large-scale and small-scale distributed photovoltaic (PV) plants. To effectively support this transition, the technological advancement and cost reduction of PV modules must be accompanied by the development of more flexible, cheaper, more efficient, and more reliable Power Electronic Converters (PEC).

To address the demanding and often conflicting requirements imposed on PECs design, this work exploits multiple methodologies to explore innovative power converter solutions for module-level grid-tied and off-grid PV applications. Starting from a critical review of the state of the art, this thesis presents key research gaps and potential opportunities for improvement in the existing solutions, and proceeds with the analysis, design, and experimental validation of new converter topologies. This work collects the outcomes of three main research projects, unified by the common framework and guiding principles, such as the close adherence to realistic PV specifications.

The first project is devoted to the design of a high step-up DC-DC converter topology for parallel power optimizers (PPOs), addressing the demanding challenge to maintain high efficiency over a wide range of operating input voltages and power levels. The proposed topology combines in an innovative way the partial power processing approach and a multi-mode control scheme, ensuring optimal

performances at a desired rated working point while preserving high efficiency out of the nominal conditions. Tests on a 700 W prototype demonstrated a 97.15 % California Energy Commission (CEC) efficiency and 97.8 % peak efficiency at the rated input voltage 39 V, and the correct operation and reduced efficiency drop across the wide 15 V–45 V input voltage range thanks to the multi-mode principle.

The second project introduces an innovative design methodology to optimize a PPO in terms of cost and weighted efficiency, while including an additional lifetime constraint under realistic mission profiles. Strong emphasis is devoted to the reliability modelling of power converters, which is often overlooked in PEC design, or based on oversimplified empirical models that neglect the physics of failure of components or the influence of mission profiles. A 500 W prototype was designed based on the optimal solution and characterized experimentally, revealing a 95.33 % CEC efficiency at the rated input voltage.

The last project investigates a quasi-resonant step-down power converter for off-grid PV-fed battery charging applications. The proposed non-isolated topology is derived from the half-bridge converter and enables the soft-switching of all its transistors thanks to a small additional inductor. The proposed converter mitigates some limitations of existing solutions related to achieving the soft-switching and high efficiency without increasing the electrical stresses and component count. A 100 W prototype is built and tested, showing a 94.5 % peak efficiency and a limited efficiency drop in the 20 %–100 % load range, thanks to the achievement of the soft-switching across most of the working points.

The exploration of innovative techniques in the design of new converter topologies allowed to achieve promising experimentally validated performance when compared to the state of the art. The innovative topologies and design methodologies investigated in this work will offer new insights to foster the research towards higher efficiency and more reliable power converters for distributed PV applications.

Keywords: Power Converters, Power Optimizers, Partial Power Processing, Multi-mode Converters, Distributed PV, Multi-objective Optimization, Reliability.