Renewable Energy 101 (2017) 168–181

Contents lists available at ScienceDirect

Renewable Energy

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

Dual-buck residential photovoltaic inverter with a high-accuracy repetitive current controller

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A R T I C L E I N F O

Article history:
Received 27 June 2016
Received in revised form
14 August 2016
Accepted 24 August 2016

Keywords:
Photovoltaic systems
Inverter
Converter
Repetitive control
Current control
Maximum power point tracking

A B S T R A C T

This paper describes a dual-buck inverter (DBI) for residential photovoltaic power conversion systems. The DBI consists of unidirectional and bidirectional switching legs, which are operated at different frequencies to attain high efficiency. The operation modes of the DBI are analyzed and a third- order control model is derived based on the analysis. Since the third-order model cannot be easily handled by the current controller design, a simple first order-model is obtained with proper assumptions and manipulations. After this, a repetitive current controller using the first-order model is designed to improve the accuracy of the current regulation in both continuous and discontinuous conduction modes. Due to the universal operation of the designed repetitive controller, the tracking accuracy for a low power reference is drastically enhanced, and this significantly improves the maximum power point tracking (MPPT) ability of the PV system. In order to verify the performance of the proposed scheme, a 3-kW DBI prototype was built and tested. The experimental results demonstrate that the proposed scheme not only reduces the total harmonic distortion of the output current, but also achieves highly accurate power tracking performance with high efficiency.

1. Introduction

Among various renewable energy sources, photovoltaic (PV) power generation systems have been receiving more and more attention, because they are reaching or already reached a grid parity depending on their installation region [1–3]. PV systems normally employ PV modules that produce unregulated dc electricity and power converters to inject dc power into the utility grid [4–9]. A power conversion circuit for a PV system usually consists of a dc-dc and a dc-ac stages. For the dc-dc stage, circuit topologies, MPPT strategies, and optimized design approaches have been studied in many articles. The most popular circuit structure for the dc-dc stage in a PV system is a typical boost converter. However, efficiency of the dc-dc stage can be considerably improved by operating the dc-dc converter in synchronous boost mode where the upper diode in the boost converter is replaced with a metal oxide semiconductor field effect transistor (MOSFET) [10,11]. In Refs. [10,12], an optimal design approach and design comparison for a PV dc-dc converter and power conversion systems are studied. Some efficiency and reliability issues have been reported in Ref. [13]. In order to improve overall system efficiency, fast and accurate MPPT strategies have been discussed in Ref. [14]. An MPPT algorithm for single-stage power converter is presented in Ref. [15]. Reference [16] compares various MPPT schemes including a distributed MPPT, a hybrid MPPT, and so on. Some articles have reported MPPT methods under partial shaded conditions [17]. During the early stage of research on PV technologies, galvanic isolation transformers were usually installed in the dc-ac stage to meet safety standards and to decouple the leakage current flowing through the PV system and the ground. However, these transformers operate at the line frequency, which makes them not only bulky, but also very expensive. The use of these transformers also reduces the overall efficiency of a PV system. In such PV systems, the well-known full-bridge inverters and half-bridge inverters have been commonly employed, because they are simple, reliable, and relatively cost effective compared to other topologies. On the other hand, transformerless power conversion topologies have been developed to improve the efficiency and the power density of the PV systems as well as lowering the production cost [18–22]. They are commonly employed for small and residential PV systems specifically where handling of the leakage current and the safety standards issues are relatively easier than larger power PV systems [5–7]. Unfortunately, traditional full-bridge inverters are not a good

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http://dx.doi.org/10.1016/j.renene.2016.08.050
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candidate for transformerless PV systems. When unipolar modulation is adapted to full-bridge inverters, the common mode voltage across the parasitic capacitance between the ground chassis of the PV panel and the dc-link rails connected to the PV cells is increased, such that a high leakage current is produced. In a full-bridge inverter with bipolar modulation, large inductor current ripples and high device switching losses are major concerns. Conventional half-bridge inverters that require higher dc-link voltages compared to full-bridge inverters are also not good alternatives in practical applications. In order to resolve these problems, many power conversion topologies that target achieving high efficiency and low leakage current have been proposed [6,7,23–25].

One of the commercially successful circuit structure is the well-known H5 topology [6,7]. This circuit consists of a full-bridge stage and a switching device at the dc bus. The lower switches of the full-bridge stage and the dc bus switching device operate at a high switching frequency, while the upper switches of the full-bridge stage is under the line frequency switching. By doing so, the efficiency of the power stage can be significantly improved, and leakage current is reasonably restrained. The highly efficient and reliable inverter concept topology has also been studied in Refs. [24,26–28]. In this topology, a bidirectional switch leg is placed between individual switching poles to prevent a free-wheeling current passing through the dc-link stage as well as implementing a three-level output voltage. Accordingly, the leakage current is considerably reduced. Neutral point clamp (NPC) types have also been widely used [29–31]. They have an inherent multi-level feature and a low common mode voltage. Thus, both a high efficiency and a low leakage current are realized. However, the potential imbalance of the dc-link capacitor voltages and the use of extra components are demerits. Reference [29] proposed an NPC-derived topology that uses eight active switches. A new pulse-width-modulation strategy was introduced in Ref. [30] to avoid a concentration of the power loss on specific components. In Ref. [31], a hybrid-bridge topology that combines an NPC leg and a half-bridge leg was proposed to reduce the dc-bus voltage. The NPC inverter with the split-inductor structure was studied for PV grid connected applications in Ref. [32]. Some studies about the so-called H6 and its variations have been continuously conducted [5,33–35]. A hybrid modulation strategy was suggested to improve the efficiency in Ref. [34]. In Ref. [35], the operational principle and the implementation issues of H6 topology were discussed.

One of the most promising topology for PV systems is the dual-buck inverter (DBI). In DBIs, two buck converters whose output terminal polarities are opposite share a common ground, and produce positive and negative currents flowing on individual paths. Compared to full-bridge inverters, DBIs are more efficient, and bring a low leakage current. There are several dual-buck structures dependent on the number of active and passive components, voltage levels, and so on. The structures include dual-buck half-bridge and full-bridge inverters, interleaved DBIs, three-level DBIs, and cascade DBIs [19,36–42].

On the other hand, the stability and the control performance are highly dependent on the controller structure in power converter applications. Regarding this issue, many control strategies have been studied including modulations, classical controllers, predictive controllers, and modern optimal controllers [43–45]. Traditionally, proportional-integral (PI) controllers have been deemed as an industrial standard because of their simple, reliable, and excellent tracking performance during transient and steady states. However, a PI controller cannot guarantee a low steady state error with a good stability in grid-tied inverter applications such as renewable energy, energy storage, and other utility grid applications where the main operating frequency is fixed to 50 or 60 Hz. It means that the control response of those inverters should be maximized at 50 or 60 Hz. However, the optimized frequency of a PI controller is not 50 or 60 Hz, but it is a dc frequency. In order to resolve this problem, some ac frequency optimized controllers have been proposed. There are mainly two approaches, the stationary and the synchronous reference frame controllers. Generally, the stationary reference frame approach is preferred in single-phase applications. One popular solution is adopting narrow bandwidth control schemes such as resonant or repetitive controllers [46–51]. A resonant controller contains a second-order resonant or a band-pass filter with infinite gain to maximize the control response at a specific frequency. While a resonant controller aims to regulate the current or voltage at a specific fundamental frequency, a repetitive controller targets multiples of the fundamental frequency including itself [52–54]. Repetitive controllers have been very well adapted into single-phase current control applications, and show an exceedingly precise current regulation performance [52,54]. Some papers have proposed compensation methods for fractional cases where the number of the digital samples for the fundamental frequency is not an integer number [55,56]. Both the repetitive and the resonant controllers are often combined with each other to obtain excellent accuracy at the steady state [57,58].

This paper describes the grid-tied DBI for small and residential PV systems. The commutation modes of the DBI are analyzed, and the modulation technique is suggested. The precise and the approximated control models are also derived. Through approximation, the third-order model including resonance is reduced to the simple first-order model that shows a good agreement with the former model in the range of current control bandwidth. A comprehensive current controller design process is also introduced. Furthermore, a high-accuracy repetitive control strategy and its qualitative design method are described in detail to achieve excellent current regulation performance.

This paper is organized as follows. In Section 2, the operation mode analysis and the control model derivation are provided. The repetitive current controller for the DBI is proposed and analyzed in Section 3. Section 4 presents the simulation results for the DBI with the proposed control scheme. Finally, the experimental results are demonstrated in Section 5.

2. Dual buck residential photovoltaic inverter

Fig. 1 represents the proposed DBI with an LCL filter containing a series damping resistor for residential PV systems. The power stage is composed of one bidirectional and two unidirectional switching legs. In Ref. [42], it is also referred as a three-level DBI. The bidirectional switching leg consists of two MOSFETs and each individual unidirectional switching leg is made of a working pair with one MOSFET and one fast recovery diode. Overall, the DBI implements unidirectional power transfer from the dc-link to the grid and it is capable of only unity power factor (PF) operations. However, this may not be a problem in residential PV applications where the reactive power compensation is not necessary. It should be noticed that the MOSFETs in the bidirectional switching leg operates with the line frequency so that the switching loss of this leg is trivial while the MOSFETs in the unidirectional switching legs are driven with a high switching frequency. It is assumed that the dc-link voltage V_{dc} may be kept constant by the operation of a dc-dc converter placed between a PV panel and the DBI. With the LCL filter configuration, the total harmonic distortion (THD) of the grid current i_s could be much lower than the filter current i_f, which is the sum of the currents in the individual switching legs, i_{f1} and i_{f2}. The biggest advantage of the DBI is that an extraordinarily high efficiency can be achieved while reducing the leakage current, which passes through the earth ground and the parasitic capacitance between the PV cells and the chassis frame of a PV panel.