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Overview of Single-Phase Grid-Connected Photovoltaic Systems

Yongheng Yang, Frede Blaabjerg

A still booming installation of solar photovoltaic (PV) systems has been witnessed worldwide. It is mainly driven by the demand of “clean” power generation. Grid-connected PV systems will become an even active player in the future mixed power systems, which are linked by a vast of power electronics converters. In order to achieve a reliable and efficient power generation from PV systems, stringent demands have been imposed on the entire PV system. It in return advances the development of power converter technology in PV systems. This paper thus takes an overview of the advancement of power electronics converters in single-phase PV systems, being commonly used in residential applications. Demands to single-phase grid-connected PV systems as well as the general system control strategies are also addressed in this paper.

Keywords: photovoltaic systems; power converters; transformerless; single-phase

Subject classification: power electronics converters

I. INTRODUCTION

Traditional power generations that are on a basic of fossil fuel resource are considered to be unsustainable in long-term national strategies. This has been one of the main driving forces for an increasing installation of renewable energies like wind power, solar PhotoVoltaic (PV) power, hydropower, biomass power, geothermal power, and ocean power, etc. into the public grids [1], [2]. Among the major renewables, the solar PV power generation has continued to expand at a rapid rate over the past five years (growth in global capacity averaging almost 55% annually) [3], [4]. As an extreme example, in Italy, 7.8% of the annual total electricity demand was covered by solar PV systems throughout 2013 [4]. In Germany, there has been around 36 GW installed by the end of 2013, where most of the PV systems are residential applications [4]-[7]. Fig. 1 further illustrates the worldwide solar PV evolution in the past years [7], which shows increasingly worldwide expectations from energy production by means of solar PV power systems. Therefore, as the typical configuration for residential PV applications, the single-phase grid-connected PV systems have been in focus in this paper in order to describe the technology catering for a desirable PV integration into the future mixed power grid.

Power electronics technology has been witnessed as the enabling technology for more renewable energies in the grid, including solar PV systems [8]. Associated by the advancements of power semiconductor devices [9], the power electronics part of the entire PV systems (i.e., power converters) holds the responsible for a reliable and efficient energy conversion from the clean, pollution-free, and inexhaustible solar PV energy. As a consequence, a vast of grid-connected PV power converters have been developed and commercialized widely [10]-[15].

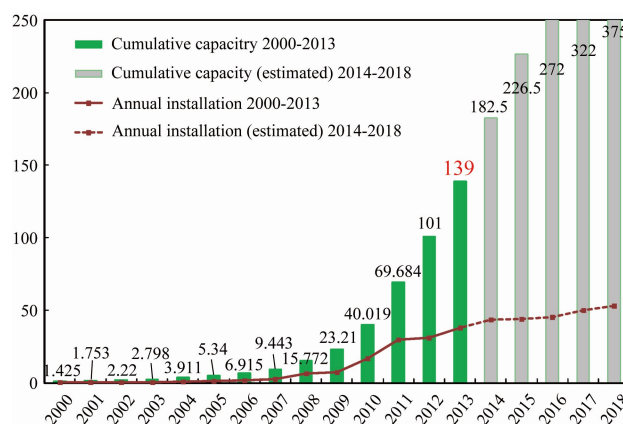


Fig. 1. Evolution of global accumulative photovoltaic capacity (Giga-Watts) from 2000 to 2013 and an estimation until 2018 in a medium scenario based on the data available on-line from EPIA.org.

However, the grid-connected PV systems vary significantly in size and power – from small scale DC module (a few hundred watts) to large scale PV power plant (up to hundred Mega-Watts). In general, the PV power converters can simply be categorized into: module-, string-, multi-string, and central converters. The multi-string and central converters are intensively used for solar PV power plants/farms as three-phase systems [16]-[18]. In contrast, the module- and string-converters are widely adopted in residential applications as single-phase systems [19], [20]. Although the PV power converters are different in configuration, the major functions of the power converters are the same, including PV power maximization, DC to AC power conversion and transfer, synchronization, grid code compliance, reactive power control, islanding detection and protection, etc. [8], [21]. It also requires advanced and intelligent controls to perform these PV features and also to

meet customized demands, where the monitoring, forecasting, and communication technology can enhance the PV integration [18], [21].

As aforementioned, the PV systems are still dominant in the residential applications, and will be even diversely spread out in the future mixed grid. Thus, the state-of-the-art developments of single-phase grid-connected PV systems are selectively reviewed in this paper. Focus has been put on the power converter advancements of single-phase grid-connected PV systems for residential applications. Demands from the grid operators and the consumers to single-phase PV systems are firstly introduced in § II. In order to meet the increasing demands, the general control structures of single-phase grid-connected PV systems are presented in § IV before the conclusion.

II. DEMANDS FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

The grid-connected PV systems are being developed at a very fast rate and will soon take a major part of power electricity generation in some areas [22], [23]. At the same time, the demands (requirements) to the PV systems as shown Fig. 2 are becoming much tougher than ever before. Although the power capacity of a PV system currently is still not comparable to that of an individual wind turbine system, similar demands to wind turbine systems are being transitioned to the PV systems [18], [21], since the number of large-scale PV systems (power plants) is continuously increased [24].

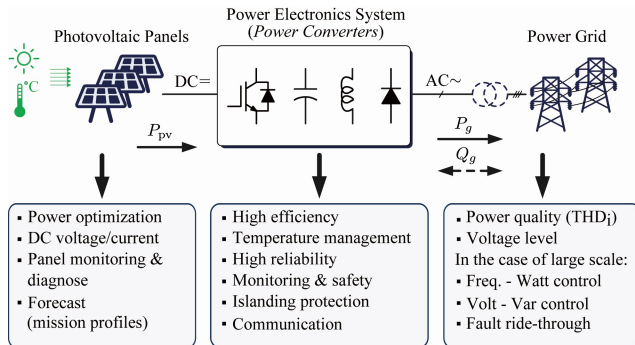


Fig. 2. Demands (challenges) for a grid-connected PV system based on power electronics converters.

Nevertheless, the demands for PV systems can be specified at different levels. At the PV side, the output power of the PV panels/strings should be maximized, where a DC-DC converter is commonly used, being a double-stage PV system. This is known as the Maximum Power Point Tracking (MPPT). In this case, the DC voltage (DC-link voltage) should be maintained as a desirable value for the inverter. Moreover, for safety (e.g., fire), the panel monitoring and diagnosis have to be enhanced at the PV side [25]. At the grid side, normally a desirable Total Harmonic Distortion (THD) of the output current should be attained (e.g., lower than 5%) [26]. In the case of large-scale PV

systems with higher power ratings, the PV systems should not violate the grid voltage and the grid frequency by means of providing ancillary services (e.g., frequency regulation). Additionally, the PV systems have to ride-through grid faults (e.g., voltage sags and frequency changes), when a higher PV penetration level comes into reality [18], [21], [27]-[33].

Since the power capacity per generating unit is relative low but the cost of energy is relative high, there are always strong demands for high efficiency in order to reduce the cost of PV energy. In respect to efficiency, the power electronics system (including passive components) counts for the most of power losses in the entire PV system. Thus, possibilities to meet the efficiency demand include using advanced semiconductor devices, intelligent control, and power lossless PV topologies. Transformerless PV technology is an example, and the transformerless PV inverters can achieve a relatively high conversion efficiency when the isolation transformers are removed [11], [26]. However, minimizing the ground current in these transformerless PV converters is mandatory for safety [11]. Moreover, reliability is of much importance in the power electronics based PV systems, as shown in Fig. 2. This is motivated by extending the total energy production (service time) and further reducing the cost of energy [8], [34]-[36]. Finally, because of exposure or smaller housing chamber, the PV converter system (power electronics system) must be more temperature insensitive (i.e. with temperature management), which is also beneficial for the reliability performance. As it has been illustrated in Fig. 2, advancing the monitoring, forecasting, and communication technologies is crucial to implement future grid-friendly PV systems into a mixed power grid.

III. POWER CONVERTER TECHNOLOGY FOR SINGLE-PHASE PV SYSTEMS

According to the state-of-the-art technologies, there are mainly four configuration concepts [2], [10], [37], [38] to organize and transfer the PV power to the grid, as it is shown in Fig. 3. As it can be seen in Fig. 3, each of the grid-connected concepts consists of series of paralleled PV panels or strings, and they are configured by a couple of power electronics converters (DC-DC converters and DC-AC inverters) in accordance to the output voltage of the PV panels as well as the power rating.

A central inverter is normally used in a three-phase grid-connected PV plant with the power larger than tens of kWp, as it is shown in Fig. 4. This technology can achieve a relatively high efficiency with a lower cost, but it requires high voltage DC cables [10]. Besides, due to its low immunity to hotspots and partial shading, power mismatch issue is significant in this concept (i.e. low PV utilization). In contrast, the MPPT control is achieved separately in each string of the string/multi-string PV inverters, leading to a better total energy yield. However, there are still mismatches in the PV panels of each string, and the multi-

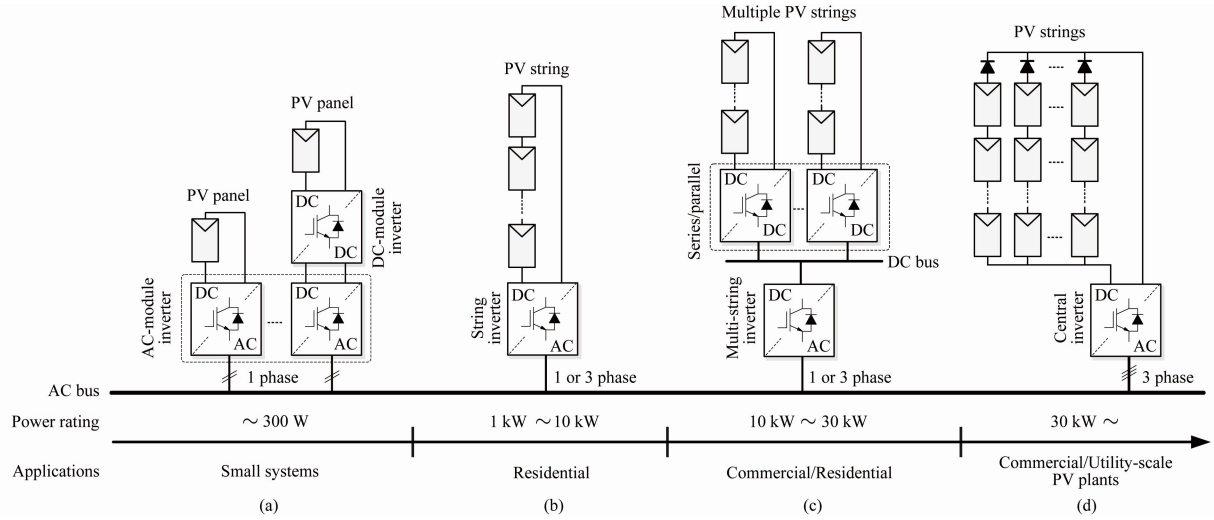


Fig. 3. Grid-connected PV system concepts: (a) AC-module PV system, (b) string inverter system, (c) multi-string inverter system, and (d) central PV inverter topology.

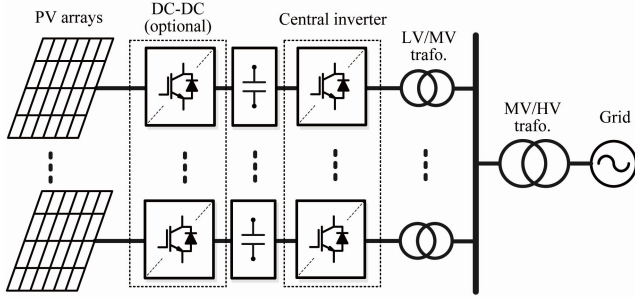


Fig. 4. Large-scale PV power plant/station based on central inverters for utility applications, where multi-level converters can be adopted as the central inverters to handle even higher power up to tens of Mega-Watts.

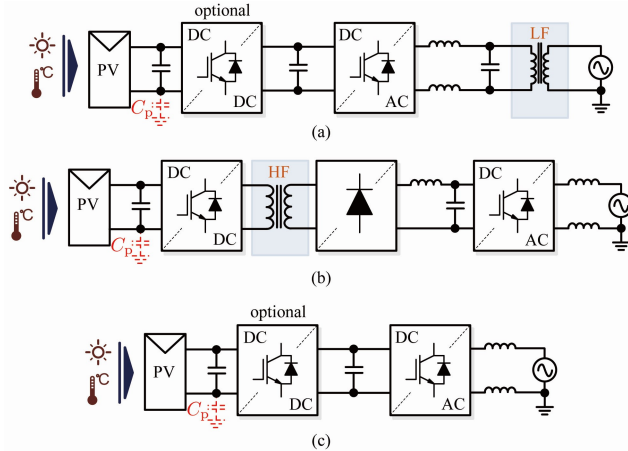


Fig. 5. Single-phase grid-connected PV systems, where the AC-module inverters, the string inverters, and the multi-string inverters are commonly used: (a) with a low-frequency (LF) transformer, (b) with a high-frequency (HF) transformer, and (c) without transformers.

string technology requires more power electronics converters, resulting in more investments. Considering the above issues, the module converters (DC-module converters and/or AC-module inverters) are developed, being a flexible solution for the PV systems of low power ratings and

also for module-level monitoring and diagnostics. This module integrated concept can minimize the effects of partial shading, module mismatch, and different module orientations, etc., since the module converter acts on a single PV panel with an individual MPPT control. However, the low overall efficiency is the main disadvantage of this concept.

It can be seen in Fig. 3 that the module concept, the string inverter, and multi-string inverters are the most common solutions used in single-phase PV applications, where the galvanic isolation for safety is one importance issue. Traditionally, an isolation transformer can be adopted either at the grid-side with low frequencies or as a high frequency transformer in such PV converters, as it is shown in Fig. 5(a) and (b). Both grid-connected PV technologies are available on the market with an overall efficiency of 93-95% [26], to which is mainly contributed by the bulky transformers. In order to increase the overall efficiency, a vast of transformerless PV converters have been developed [10], [11], [26], which are selectively reviewed in the following.

A. Transformerless AC Module Inverters (Module Integrated PV Converters)

In the last years, much more efforts have been devoted to reduce the number of power conversion stages in order to increase the overall efficiency, as well as increase the power density, being the single-stage AC-module PV inverters. By doing so, the reliability and thus the cost can be reduced. Fig. 6 shows the general block diagram of a single-stage grid-connected AC-module PV topology, where all the desired functionalities shown in Fig. 2 have to be performed. It should be noted, the power decoupling in such a single-stage topology is achieved by means of a DC-link capacitor, C_{dc} , in parallel with the PV module [10], [11].

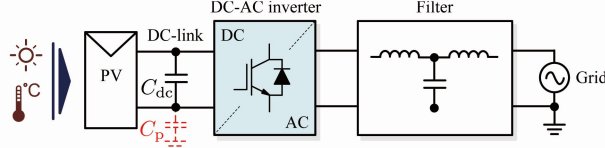


Fig. 6. General block diagram of a single-stage single-phase PV topology (AC module/string inverter system).

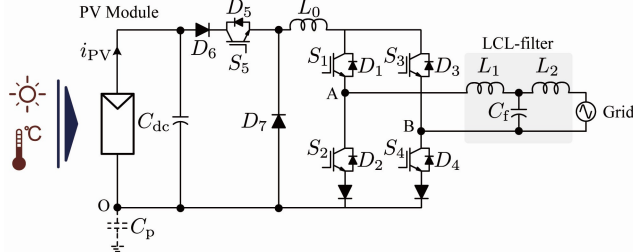


Fig. 7. A universal single-stage grid-connected AC-module inverter with an LCL-filter based on the concept proposed by B.S. Prasad, *etc.* appeared in IEEE Trans. Energy Conversion – 23(1), p. 128-137, Mar. 2008.

Since the power of a single PV module is relative low and is strongly dependent of the ambient conditions (i.e., solar irradiance and ambient temperature), the trend for AC-module inverters is to integrate either a boost or a buck-boost converters into a full-bridge or half-bridge inverter in order to achieve an acceptable DC-link voltage [39]-[45]. As it is presented in [39], a single-stage module integrated PV converter can operate in a buck, boost, or buck-boost mode with a wide range of PV panel output voltage. This AC-module inverter is shown in Fig. 7, where an LCL-filter is used to achieve a satisfactory total harmonic distortion of the injected current. A variant AC-module inverter has been introduced in [40], which is however a resultant integration of a boost converter and a full-bridge inverter. The main drawback of the integrated boost AC-module inverter is that it will introduce a zero-cross current distortion. In order to solve this issue, the buck-boost AC module inverters are preferable [41]-[44].

Fig. 8 shows two examples of the buck-boost AC-module inverter topologies for single-phase grid-connected PV applications. In the AC-module inverter shown in Fig. 8(a), each of the buck-boost converters generates a DC-biased unipolar sinusoidal voltage, which is 180° out of phase to the other, so as to alleviate the zero-cross current distortions. Similar principles are applied to the buck-boost integrated full-bridge inverter, which operates for each half-cycle of the grid voltage. However, as shown in Fig. 8(b), this AC-module inverter is using a common source.

In addition to the above topologies that are mainly based on two relatively independent DC-DC converters integrated in an inverter, other AC-module inverters are proposed in the literature. Most of these solutions are developed in accordance to the impedance-admittance conversion theory as well as an impedance network [46]-[50]. The Z-source inverter is one example, which is able to boost up the voltage for a full-bridge inverter by adding an LC impedance network, as shown in Fig. 9. Notably, the Z-source inverter was mostly used in three-phase applications in the past.

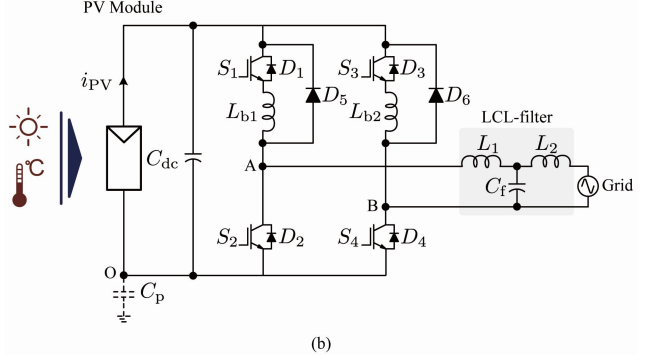
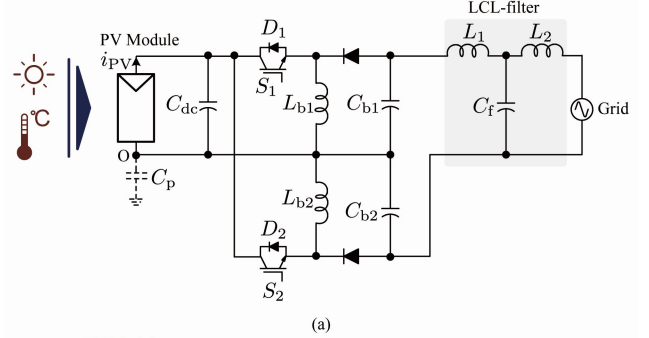


Fig. 8. Buck-boost integrated AC-module inverters with an LCL filter: (a) differential buck-boost inverter based on the concept proposed by N. Vazquez, *etc.* appeared in Proc. of APEC, pp. 801-806, 1999 and (b) buck-boost integrated full-bridge inverter based on the concept proposed by C. Wang appeared in IEEE Trans. Power Electron. -19(1), pp. 150 - 159, 2004

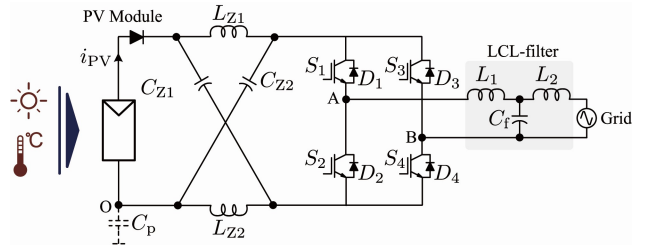


Fig. 9. Single-phase Z-source based AC-module inverter with an LCL filter.

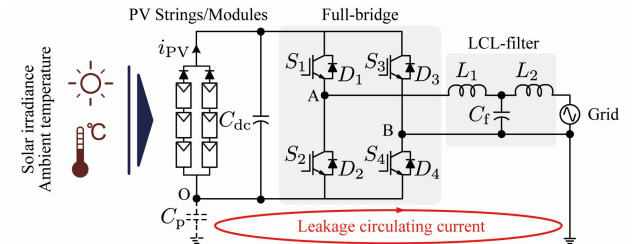


Fig. 10. Single-phase transformerless full-bridge string inverter with an LCL filter, which also indicates the ground current circulating path through the parasitic capacitor C_p .

B. Transformerless Single-stage String Inverters

The above-discussed AC-module inverters with an integration of a DC-DC boosting converter are suitable for use in low power applications. When it comes to higher power ratings (e.g., 1 ~ 5 kWp), the compactness of AC-module inverters is challenged. In such applications, the most commonly used inverter topology is the single-phase Full-

Bridge (FB) string inverter due to its simplicity in terms of less power switching devices. Fig. 10 depicts the hardware schematics of a single-phase FB string inverter with an *LCL* filter, for a better power quality. It is also shown in Fig. 10 that a leakage current will circulate in the transformerless topology, requiring a specifically designed modulation scheme to minimize. Conventional modulation methods for the single-stage FB string inverter topology include a bipolar modulation, a unipolar modulation, and a hybrid modulation [26]. Considering the leakage current injection, the bipolar modulation scheme is preferable [26], [51]. Notably, optimizing the modulation patterns is an alternative to eliminate the ground (leakage) currents [52].

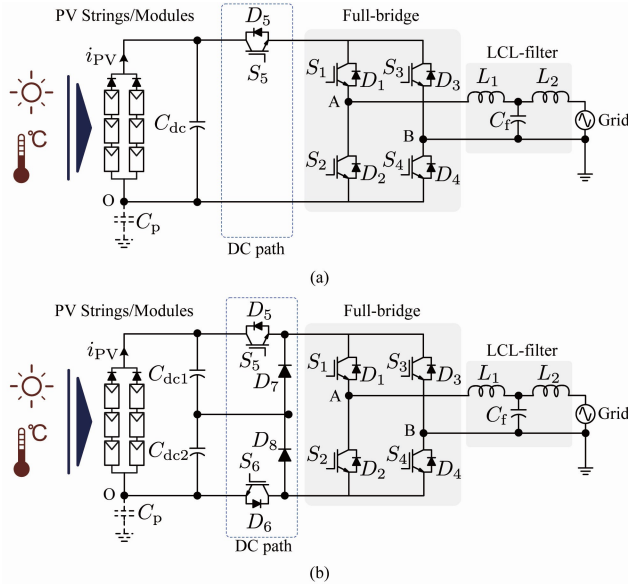


Fig. 11. Transformerless string inverters derived from the full-bridge inverter by adding a DC path: (a) H5 inverter topology proposed by M. Victor, *etc.*, U.S. Patent 20050286281 A1, Dec 29, 2005. and (b) H6 inverter topology proposed by R. Gonzalez, *etc.*, appeared in IEEE Trans. Power Electron. – 22(2), pp. 693-697, Mar. 2007.

Transformerless structures are mostly derived from the FB topology by providing an AC path or a DC path using additional power switching devices. This will result in an isolation between the PV modules and the grid during the zero-voltage states, thus leading to a low leakage current injection. Fig. 11 shows two examples of single-stage transformerless PV inverters derived from the single-phase FB topology by providing a DC path [53], [54]. Thanks to the extra DC bypass, the PV strings/panels are isolated from the grid at zero-voltage states. Alternatively, the isolation can be achieved at the grid side by means of adding an AC path. As exemplified in Fig. 12(a), the Highly Efficient and Reliable Inverter Concept (HERIC) string inverter [55] has the same number of power switching devices as that of the H6 inverter, but it provides an AC path to eliminate the leakage current injection. Similarly, the Full-Bridge Zero Voltage Rectifier (FB-ZVR) topology is proposed in [56], where the isolation is attained by adding a zero voltage rectifier at the AC side, as shown in Fig. 12(b).

It should be pointed out that there are also many other transformerless topologies reported in the literature in addition to the above solutions by means of adding an extra path [26], [52], [57]-[60]. Taking the Conergy string inverter as an example, which is shown in Fig. 13, the single-phase transformerless string inverter can be developed based on the multi-level power converter technology [26], [58], [59].

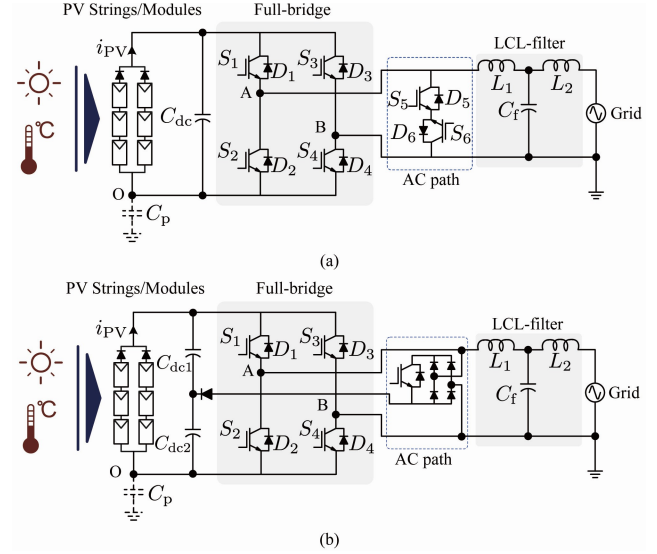


Fig. 12. Transformerless string inverters derived from the full-bridge inverter by adding an AC path: (a) highly efficient and reliability inverter concept (HERIC) topology proposed by H. Schmidt, *etc.*, U.S. Patent 7046534, 2006 and (b) full-bridge with a zero voltage rectifier (FB-ZVR) proposed by T. Kerekes, *etc.* appeared in IEEE Trans. Ind. Electron. – 58(1), pp. 184-191, Jan. 2011.

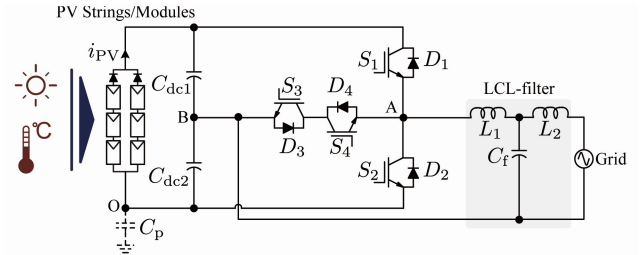


Fig. 13. A transformerless string inverter derived from neutral point clamped topology – Conergy neutral point clamped inverter with an *LCL* filter based on the concept proposed by P. Knaup, International Patent Application, WO 2007/048420 A1, May 3, 2007.

C. DC-Module Converters in Transformerless Double-Stage PV Systems

The major drawback of single-stage PV topologies is that the output voltage range of the PV panels/strings is limited especially in low power applications (e.g. AC-module inverters), which thus will affect the overall efficiency. The double-stage PV technology can solve this issue since it consists of a DC-DC converter that is responsible for amplifying the PV module low voltage to a desirable level for the inverter stage. Fig. 14 shows the general block diagram of a double-stage single-phase PV topology. The DC-DC converter also performs the MPPT control of

the PV panels, and thus extended operating hours can be achieved in a double-stage PV system. The DC-link capacitor C_{dc} shown in Fig. 14 is used for power decoupling, while the PV capacitor C_{pv} is for filtering.

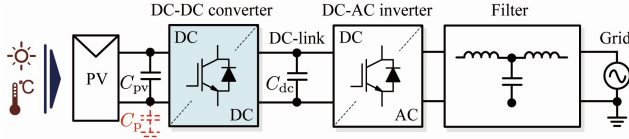


Fig. 14. General block diagram of a double-stage single-phase PV topology (with a DC-DC converter).

In general, the DC-DC converter can separately be included between the PV panels and the DC-AC inverters that can be the string inverters discussed above or a simple half-bridge inverter. The following illustrates the double-stage PV technology consisting of a DC-DC converter and a full-bridge inverter. Fig. 15 shows a conventional double-stage single-phase PV system, where the leakage current has to be minimized as well. However, incorporating the boost converter will decrease the overall conversion efficiency. Thus, variations of the double-stage configuration have been introduced by means of a time-sharing boost converter or a soft-switched boost converter [61], [62]. The time-sharing boost converter shown in Fig. 16 is a dual-mode converter, where the switching and conduction losses are reduced, leading to a satisfactory efficiency.

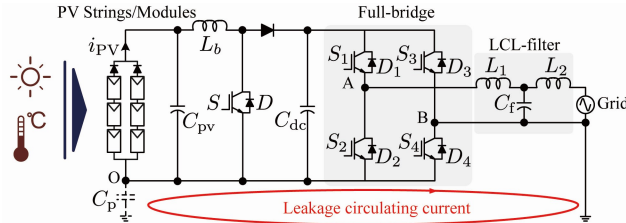


Fig. 15. Conventional double-stage single-phase PV topology consisting of a boost converter and a full-bridge inverter with an LCL filter.

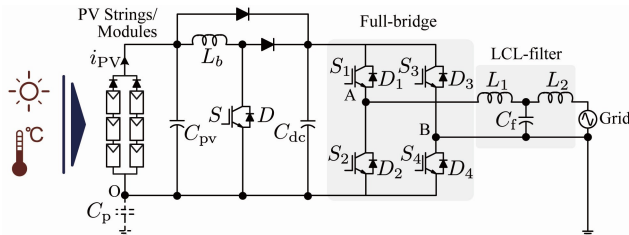


Fig. 16. Double-stage single-phase PV topology using a time-sharing boost converter and a full-bridge inverter with an LCL filter based on the concept proposed by K. Ogura, *etc.*, appeared in Proc. of IEEE PESC, pp. 4763-4767, 2010.

An alternative to improve the efficiency can be achieved using a DC-DC converter with parallel inputs and series outputs in order to process the source energy one and a half times instead of two times. This topology has been introduced in [63], and it is shown in Fig. 17. It should be pointed out that the voltage step-up gain of the DC-DC converter is also improved at the same time. In addition,

the impedance network based DC-DC converters (e.g., the Z-source and Y-source networks) might be another promising solution for single-phase double-stage PV systems, due to the high step-up voltage gain [64]-[67].

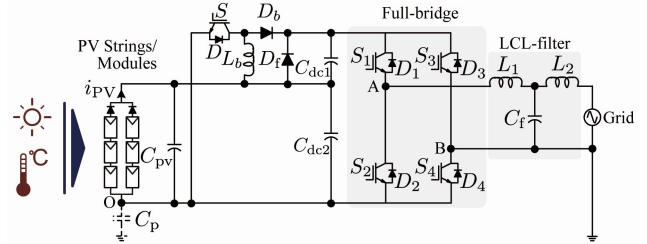


Fig. 17. Double-stage single-phase PV topology with a parallel-input series-output bipolar DC output converter and a full-bridge inverter based on the concept proposed by R. West, U.S. Patent 2008/0037305 A1, Feb. 14, 2008.

IV. CONTROL OF SINGLE-PHASE GRID-CONNECTED PV SYSTEMS

The control objectives of a single-phase grid-connected PV system [68] can be divided into two major parts: a) PV-side control with the purpose to maximize the power from PV panels and b) grid-side control performed on the PV inverters with the purpose to fulfil the demands shown in Fig. 2. A conventional control structure for such a grid-connected PV system thus consists of two-cascaded loop in order to fulfil the demands [32], [68] – the outer power/voltage control loop generates the current references and the inner control loop is responsible for shaping current, where thus the power quality is maintained, and also performing various functionalities, as shown in Fig. 18.

Fig. 19 shows the general control structure of a single-phase single-stage grid-connected PV system, where the PV inverter has to handle the fluctuating power (i.e., MPPT control) and also to control the injected current according to the specifications shown in Fig. 18. As it can be observed in Fig. 19, the control can be implemented in both stationary and rotating reference frames in order to control the reactive power exchange with the grid, where the Park transformation ($dq \rightarrow \alpha\beta$) or inverse Park transformation ($\alpha\beta \rightarrow dq$) are inevitable. In terms of simplicity, the control in the stationary reference frame ($\alpha\beta$ -reference frame) is preferable, but it requires an orthogonal system to generate a “virtual” system, which is in-quadrature to the real grid. In the dq -reference frame, the MPPT control gives the active power reference for the power control loop based on Proportional Integrator (PI) controllers, which then generate the current references as shown in Fig. 19(b). The Current Controller (CC) in the dq -reference frame can be PI controllers, but current decoupling is required. In contrast, enabled by the single-phase PQ theory [32], [69], the reference grid current i_g^* can be calculated using the power references and the in-quadrature voltage system. In that case, the PI controller will give an error in the controlled grid current. The controller (i.e., CC) should be

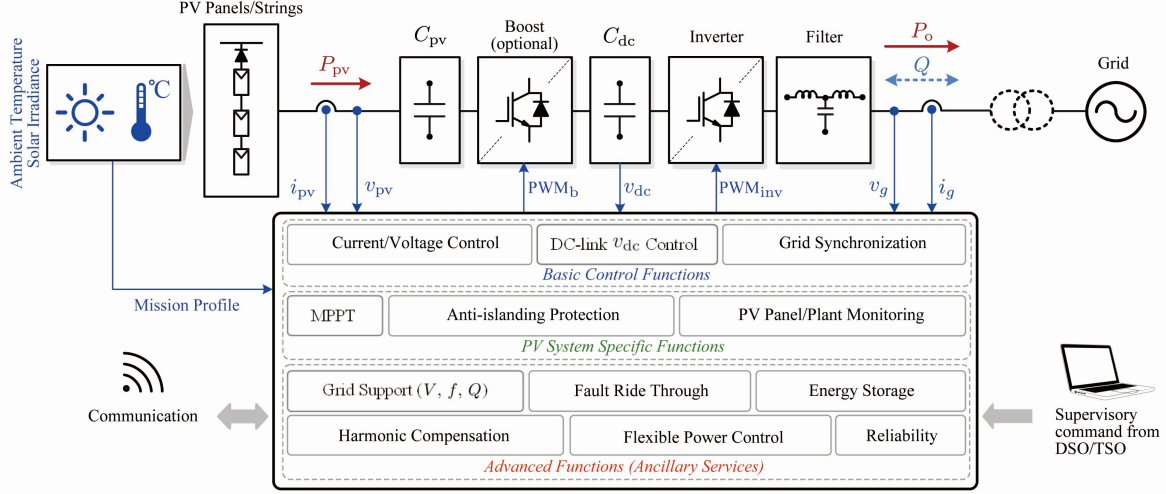


Fig. 18. General control blocks (control objectives) of a grid-connected single-phase PV system.

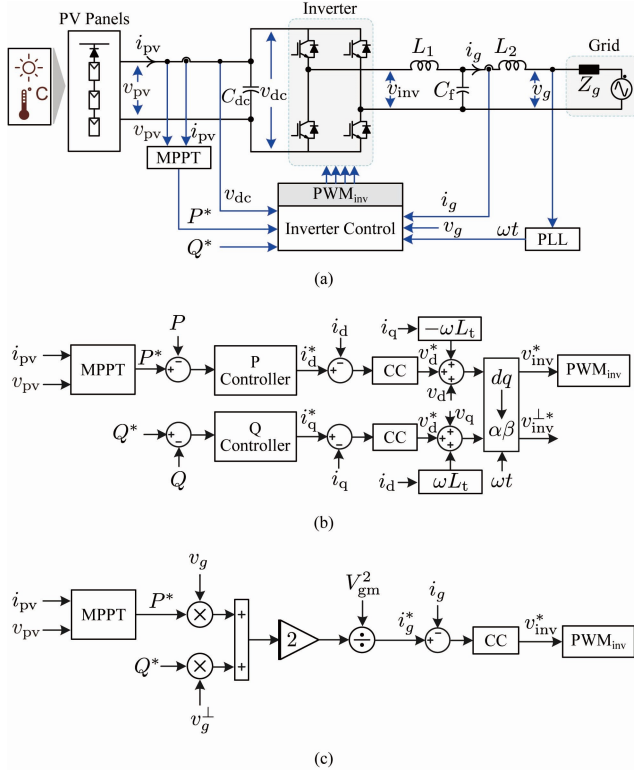


Fig. 19. General control structure of a single-phase single-stage full-bridge PV system with an *LCL* filter and reactive power injection capability (CC – Current controller, PLL – Phase locked loop): (a) hardware schematics, (b) control block diagrams in the *dq*-reference frame, and (c) control block diagrams in the *αβ*-reference frame.

designed in the *αβ*-reference frame. For example, a Proportional Resonant (PR) controller, a Repetitive Controller (RC), and a Dead-Beat (DB) controller [68], [70]-[73] can directly be adopted as the CC shown in Fig. 19(c). Notably, since the CC is responsible for the current quality, it should be taken into account in the controller design and the

filter design (e.g., using high order passive filter, *LCL* filter). By introducing harmonic compensators [26], [32], [68], [70] and adding appropriate damping for the high order filter [74], [75], an enhancement of the CC tracking performance can be achieved. Similar control strategies can be applied to the double-stage system, as shown in Fig. 20. The difference lies in that the MPPT control is implemented on the DC-DC converter, while the other functionalities are performed on the control of the PV inverter. There are other control solutions available for single-phase grid-connected PV systems [76]-[78]. For example, the instantaneous power is controlled in [77], where the synthesis of the power reference is a challenge; in [78], a one-cycle control method has been applied to single-stage single-phase grid-connected PV inverters for low power applications.

It should be noted that the injected grid current is demanded to be synchronized with the grid voltage as required by the standards in this field [68]. As a consequence, the grid synchronization as an essential grid monitoring task will strongly contribute to the dynamic performance and the stability margin of the entire control system. The grid synchronization is even challenged in single-phase systems, as there is only one variable (i.e. the grid voltage) that can be used for synchronization. Nevertheless, different methods to extract the grid voltage information have been developed in recent studies [26], [68], [79]-[82] like the zero-crossing method, the filtering of grid voltage method, and the Phase Locked Loop (PLL) techniques, which are the promising solutions. In addition to the phase of the grid voltage, other grid condition information is also very important for the control system to perform special functionalities, e.g., low voltage ride through [27], [32], where the grid voltage amplitude has to be monitored. Thus, advancing the monitoring technology is another key to a grid-friendly integration of grid-connected PV systems.

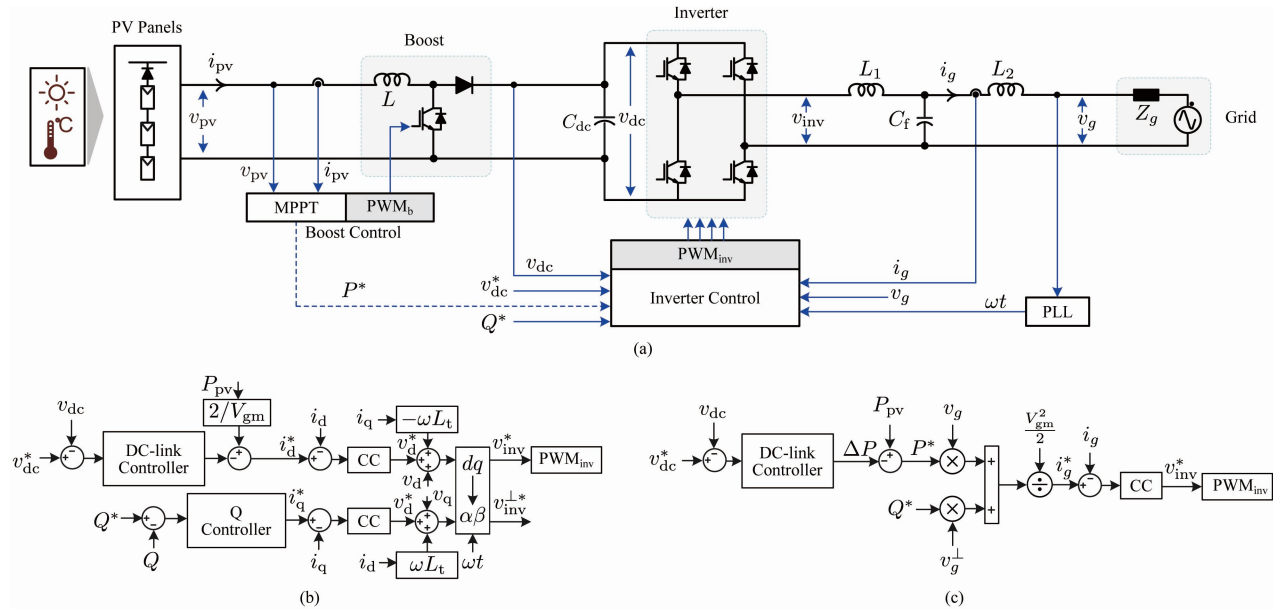


Fig. 20. General control structure of a single-phase double-stage grid-connected PV inverter with an LCL filter and reactive power injection capability (CC – Current controller, PLL – Phase locked loop): (a) hardware schematics, (b) inverter control diagrams in the dq -reference frame, and (c) inverter control diagrams in the $\alpha\beta$ -reference frame.

V. CONCLUSIONS

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