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Overview of Industrial Inverters for Photovoltaic Applications

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Abstract

As the growth of India is goes on increases rapidly power demand is also increases. To meet this power demand it is not good to only depend on the available power sources such as dam cola power plant etc. On the other hand there is huge development in renewable energy sources has been done. So one solution to fulfill power demand is to interconnect renewable energy sources with grid. To interconnect renewable sources with grid power converter plays an important role. This paper presents the overview of industrial inverters for photovoltaic application. What are the conventional topologies are present that introduce in section II and advance inverter topologies such as ac-dc and dc-dc are introduced in section III.

Keywords- String Inverter, Multistring Inverter, Central Topology, AC modular Topology, PV system

I. INTRODUCTION

As the PV installed capacity in India goes on increase there is a continuous evolution of the PV power conversion stage. Gradually, PV power converters have become extremely, compact, and reliable, allowing the maximum power to be obtained from the sun in domestic, commercial, and industrial applications [1], [2]. The PV converter industry has evolved rapidly from childhood to adulthood in the last two decades and has become a distinct power converter category in its own right. One of the drivers behind this progress is that the PV converter market demanded very hard to- meet specifications, including high efficiency (above 98%), long warranty periods (to get closer to PV module warranties of 25 years), high power quality, transformer less operation, leakage current minimization (imposes restrictions on the topology or modulation), and special control requirements such as the MPPT. Another driver behind this development is the fact that, for long time, the power converter represented a small fraction of the cost of the whole PV system due to high PV module prices, allowing PV inverter manufacturers room for developing higher performance and more sophisticated topologies. These topologies usually included more power electronics devices than the classic topologies used in general applications, which have added control degrees of freedom that can be used to make the inverter operation more efficient, as will be addressed later in this article.

The development of new PV converter topologies has also been motivated by manufacturers' search for proprietary technology to differentiate themselves from their competitors and achieve a competitive advantage in a growing PV converter market. This has led to a wide range of new and different power converter topologies specially designed for PV applications, which will be presented and analyzed in this article.

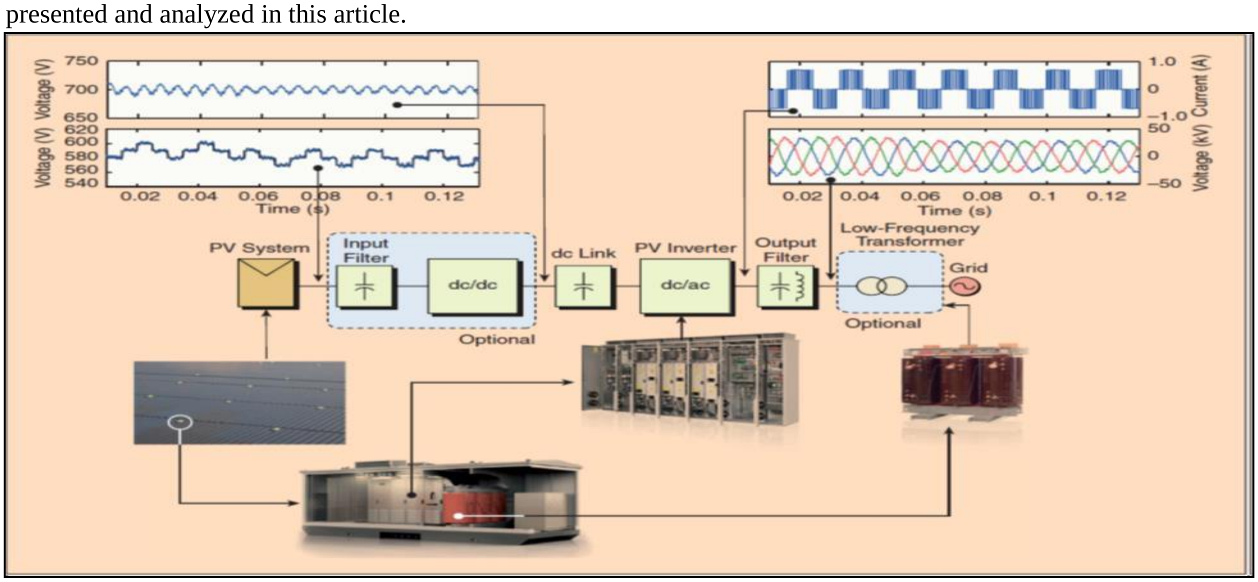

Fig. 1: The generic structure of a grid-connected PV system

II. INDUSTRIAL PV INVERTERS

The evolution in power converter technology for PV applications, driven by the growth in the PV installed capacity and the search for the ultimate PV inverter, has led to the existence of a wide variety of power converter topologies used in practice. Figure 3 shows several industrial PV inverter topologies for central, string, multistring, and ac-module configurations, which will be analyzed in this section.

A. String Inverter Topology

The most common string inverter topology is the full- or H-bridge inverter. Several modified and enhanced versions have found their way into the market [3].

The H-bridge with a grid-side low frequency transformer features a simple power circuit, galvanic isolation, and voltage elevation provided by the transformer, which enables a larger range of input voltages. This converter can be controlled with three-level carrier-based pulse-width modulation (PWM) techniques since the common mode voltages cannot generate a leakage current due to isolation. The bypass switching state (zero voltage level) prevents a reactive current flow between the filter inductor and the dc-link capacitor. Nevertheless, the bulky transformer has several disadvantages (low power density and lower efficiency), making this topology less popular with time.

The transformer less H-bridge, also known as an H4 inverter (shown in a two stage configuration with a boost dc–dc stage), gets rid of the low-frequency transformer by splitting the grid inductor into the phase and neutral wires of the systems and using a bipolar PWM (two-level) to solve the issues of the switched common-mode voltage and leakage currents and by using a boost stage for a wider input voltage range.

The downside is that the two-level modulation reduces the power quality at the grid connection and lowers the efficiency since there is a reactive current flow between the passive elements of the circuit at zero voltage through the freewheeling diodes as the dc-link capacitor is not isolated from the grid at any time.

The H-bridge with the HF isolated dc– dc stage is composed of a MOSFET full bridge inverter, an HF transformer, and a diode full-bridge rectifier. This approach greatly reduces the size of the converter, improving the power density compared to low-frequency transformer-based topologies. However, the additional converter stages introduce higher losses.

To overcome the problem of the reactive current transfer between the grid filter and the dc-link capacitor in transformer less H-bridge string inverters during freewheeling, several proprietary solutions have been introduced by different manufacturers [3]–[5]. The H5 string inverter by SMA adds an additional switch between the dc-link and the H-bridge inverter to open the current path between passive components, increasing the efficiency and reducing the leakage current. The highly efficient and reliable inverter concept (HERIC) introduced by Sunway's uses instead a bidirectional switch that bypasses the whole H-bridge inverter, separating the grid filter from the converter during freewheeling. The H6 topology introduced by Ingeteam [6] adds an additional switch in the negative dc bar to the H5 topology. Two versions were introduced: one with a diode connected in parallel to the dc side of the H-bridge of the H6 topology, called the H6D1, and the H6D2, which adds two auxiliary freewheeling diodes instead of one. Both allow freewheeling without interaction between passive components while enabling a unipolar output compared to the H5. The difference between the H6D1 and the H6D2 is that in the former, the additional switches block the total dc voltage, while in the latter, they only block half. The three-level NPC inverter (3L-NPC) also has several modified and enhanced versions for PV string inverters [7]. The advantage of the 3L-NPC over the H-bridge is that it provides a three-level output without a switched common-mode voltage since the neutral of the grid is grounded to the same potential as the midpoint of the dc link. This enables transformer less operation without the problem of the leakage currents and modulation methods that do not use the potential of the converter. The main drawback compared to the H-bridge is that it requires a total dc link of double the voltage to connect to the same grid. Hence, more modules need to be connected in series or an additional boost stage is required.

A full-bridge of two 3L-NPC legs was introduced by ABB, resulting in the 5LHNPC inverter [8]. As with the H-bridge, this converter also requires a symmetrical grid filter distributed between the grid phase and grid neutral wires. A special modulation technique can achieve a line frequency common-mode voltage; hence, no leakage currents are generated while enabling transformer less operation.

The T-type or three-level transistor clamped string inverter was introduced by Conergy. The converter can clamp the phase of the grid directly to the neutral to generate the zero voltage level using a bidirectional power switch. For the same reason as the 3L-NPC, it can operate transformer less. The main difference is that it does not require the two additional diodes of the 3L-NPC. The bidirectional switches block each half of the voltage blocked by the phase-leg switches. The asymmetric cascaded H-bridge was introduced by Mitsubishi [9] and features three series-connected H-bridge cells operating with unequal dc voltage ratios (1:2:4). The PV system is connected through a boost dc–dc stage to only one of the H-bridge cells, which is the only one processing active power to the grid. The other two cells use floating dc links for power quality improvement through the generation of 13 voltage levels. This enables a reduction of the switching frequency without compromising the power quality. The topology requires a bidirectional bypass switch connected to the large cell to reduce the changing potential between the PV system and the ground to reduce the possibility of leakage currents and enable transformer less operation.

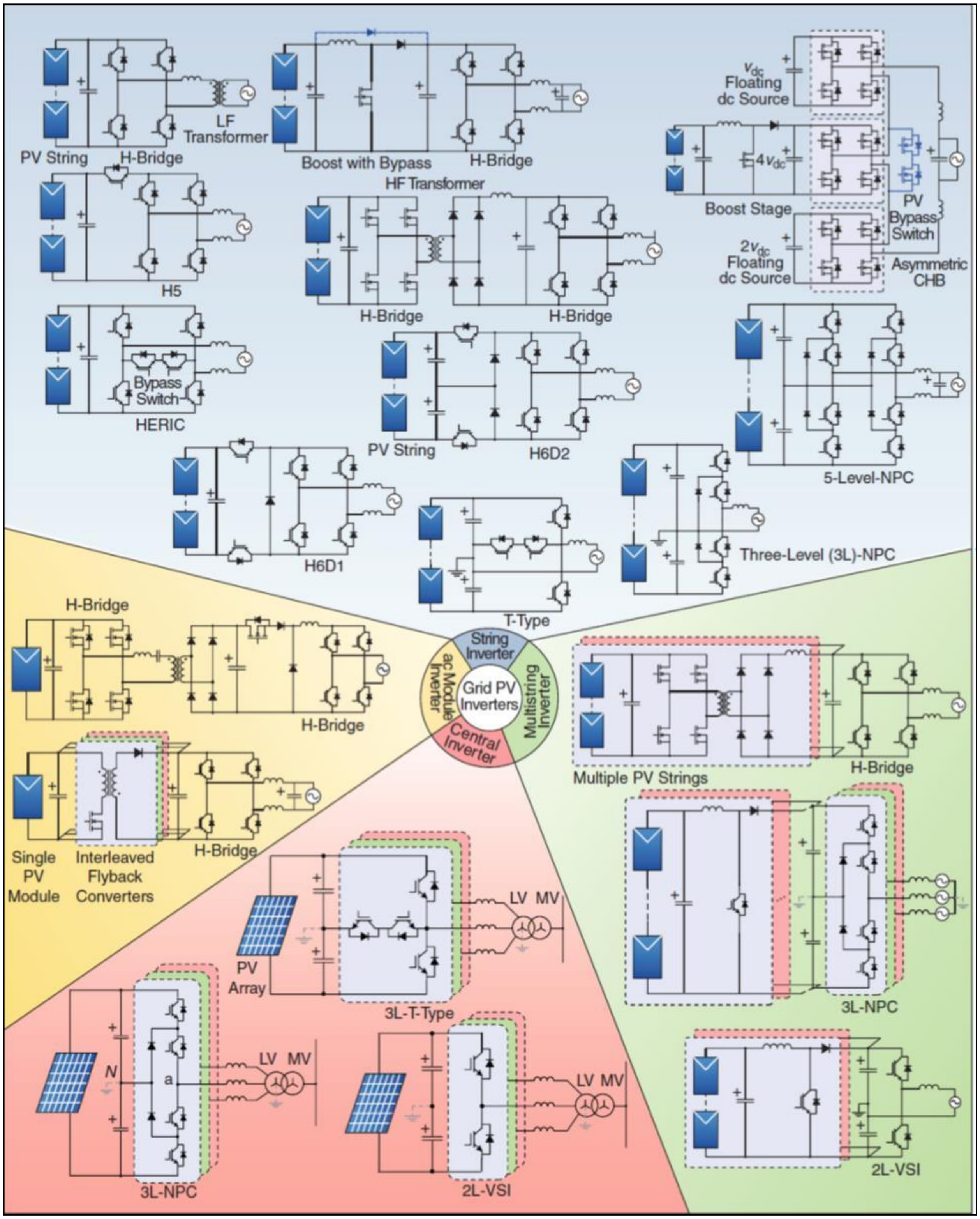

Fig. 3: Industrial PV inverter topologies for central, string, multistring, and ac-module

B. Multistring Topology

The main difference between the multistring and string configuration is that multistring is exclusively a two-stage system composed by more than one dc–dc stage [10]. Hence, all inverter topologies in the "String Inverter Topologies" section could be used in a multistring configuration. Like with string inverters, the same combinations of isolated and transformer less configurations apply with or without symmetric grid filters.

One of the first multistring inverters introduced in practice was the half bridge inverter with boost converters in the dc–dc stage by SMA [10]. Other topologies that have followed include the H-bridge, the H5, the three-phase two-level voltage–source inverter (2L-VSI), the 3L-NPC, and the three-phase three-level T-type converter (3L-T) [3]. Figure 3 shows some examples of practical multistring configurations. The most common dc–dc stages used for multistring configurations are the boost converter and the HF isolated dc–dc switch mode converter based on an H-bridge, HF transformer, and diode rectifier.

C. Central Topologies

Central inverter configurations are mainly used to interface large PV systems to the grid. The most common inverter topology found in practice is the 2L-VSI, composed of three half-bridge phase legs connected to a single dc link. The inverter operates below 1,000 V at the dc side (typically between 500 and 800 V), limited by the PV module's insulation, which prevents larger strings. Grid connection is done through a low-frequency transformer to elevate the voltage already within the collector of the power plant to reduce losses. More recently, the three phase 3L-NPC and the three-phase 3LT converter have been also used for this configuration, as shown in Figure 3. The characteristics, advantages, and disadvantages analyzed for the single-phase versions of these topologies for PV string systems also hold for the central inverter version.

D. AC-Module Topology

A commercial ac-module topology is the interleaved fly-back converter, developed by Enphase Energy [11] and currently commercialized by Siemens, shown in Figure 3. The fly-back converter performs MPPT and voltage elevation and provides galvanic isolation while the H-bridge inverter controls the dc-link voltage (output voltage of the fly-back), grid synchronization, and active/reactive power control. Several fly-back converters are connected in parallel, which enables a higher switching frequency, resulting in a further reduction of the HF transformer and, hence, a very compact inverter. It also allows for a reduction in the current ripple both at the input and output of the dc–dc stage due to the phase-shifted carrier modulation, extending the life span of the capacitors.

Another commercial ac-module integrated converter, shown in Figure 3, includes a resonant H-bridge stage with an HF isolation transformer and a diode bridge rectifier as a dc–dc converter instead of the fly-back developed by Enecsys [12]. The H-bridge dc–dc stage has better power conversion properties compared to the fly-back.

III. RECENT ADVANCES ON GRID CONNECTED PV INVERTERS

The last decade has seen marked progress in the research and development of new power converter topologies for PV applications. The main research efforts have concentrated on the highest possible efficiency, power density, and reliability of the converter to further increase the overall performance of the PV installation. In the majority of cases, the newly emerged topologies are the full-power converters in which the whole amount of the PV panel (or PV string) power has to be processed.

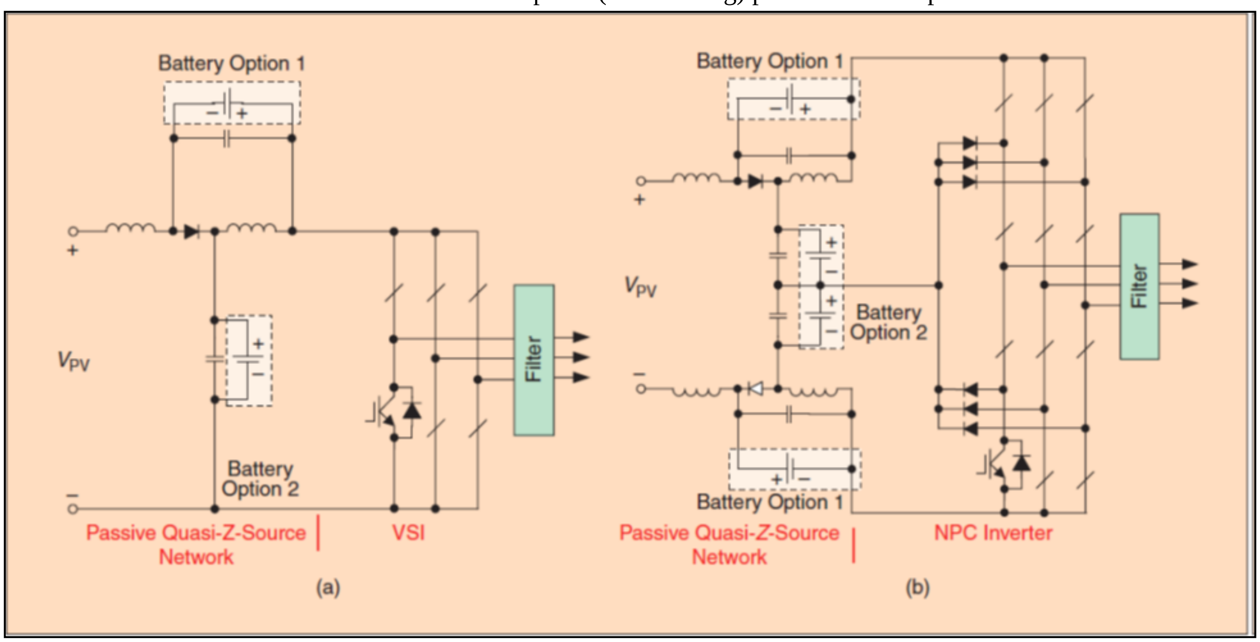

Fig. 4: Generalized topologies of the most popular single-stage buck-boost inverters: (a) two-level and (b) 3-L NPC quasi-Z-source inverters.

A. Advances in DC-AC Converter for PV System

As shown in Figure 1, in a typical PV inverter, the two-stage power conversion is currently the most common approach to cope with a wide input dc voltage range produced by the PV panel. In that case, the PV power conditioning system consists of the front-end dc–dc converter for the MPPT and the inverter to feed the power to the ac load or grid [13] – [15]. However, this multiple-stage power conversion system could lower the energy efficiency and reliability of the PV installation.

To overcome these problems, in 2003, the novel family of single-stage buck–boost inverters was introduced by Prof. Peng [16], with the most promising topology being the quasi-Z-source inverter (QZSI) [17]. This buck–boost inverter is a combination of the two-port passive quasi-impedance network with a 2L-VSI [Figure 4(a)]. The distinctive feature of the QZSI is that it can boost the input voltage by using an extra switching state—the shoot-through state. The shoot-through state is the simultaneous conduction of both switches of the same phase leg of the inverter. This operation state is forbidden for the traditional VSI because it causes the short circuit of the dc-link capacitors. In the QZSI, the shoot-through state is used to boost the magnetic energy stored in the inductors of the quasi-Z-source network without short-circuiting the dc capacitors. This increase in inductive energy, in turn, provides the boost of the voltage across the inverter during the traditional operating states (active states). The QZSI has the input inductor that buffers the source current, which means that during the continuous conduction mode, the input current never drops to zero, thus featuring the reduced stress of the input voltage source. Moreover, the properties of the QZSI allow the energy storage (typically the battery) to be connected in parallel with one of the capacitors of the quasi-Z-source network [18]. The state of charge of the battery is then controlled by varying the shoot-through duty cycle of the inverter switches. Therefore, the simple energy storage system for covering the peak power demands could be used in the QZSI without any additional circuits. The two-level QZSI could be easily extended to the multilevel topology, as presented in Figure 4(b). The three level NPC QZSI has similar advantages as the two-level topology; moreover, it could be used with single or multiple PV urges [19]. As in the case of two-level QZSI, the short term energy storage (battery) can be connected in parallel either with the external or internal capacitors of the quasi-Z-source-network. Thanks to all of these advantages, the QZSI is referred to as one of the most promising power conversion approaches for future PV power conditioners.

Another hot topic regarding recent PV inverters is the use of different multilevel converter topologies to enable medium-voltage (MV) grid connection. Most commercial topologies shown in Figure 3 are in fact multilevel converters (e.g., three-level H-bridge, three-level NPC, three-level T-type, and their derivatives). However, all of these converters connect to LV grids since PV strings cannot surpass the 1,000-V limit due to the module insulation standard. Therefore, to be able to connect to MV grids, the multilevel converters must be able to support several individual strings at the dc side and connect them somehow in series through the converter power stages to the output. Several alternative topologies have been introduced to achieve a high number of levels and reach MV operation [20]. An advantage of using multilevel converters as PV inverters is related to the output waveform's high quality, which reduces the grid connection filter requirements, leading to a compact design for low-power applications (usually domestic rooftops). In addition, the use of multilevel converters can lead to avoidance of the additional boost converter in the input or the step-up transformer in the output, eliminating the additional power conversion stages and improving the efficiency of the system. On the other hand, some multilevel converter topologies, such as the cascaded H-bridge converter or the modular multilevel converter, can take advantage of splitting the PV array system to achieve higher efficiency values using independent MPPT algorithms. This could be interesting for central inverters of PV medium and high-power plants [21].

Another research focus involves developing PV inverters with additional energy storage capability usually based on batteries. These hybrid systems present the advantages of improving the frequency and voltage regulation, storing the energy if it is not demanded by local loads, and supplying this energy when required, increasing the overall system operation (usually called peak load shaving). These systems are mainly focused for stand-alone systems, household applications, or weak grid-connected applications of large PV plants [22]. The use of hybrid PV batteries can already be found as a commercial product for household applications (see, for instance, the Sunny Boy 3600/5000 Smart Energy by SMA) [23].

This trend emerges as an important field of development for the future. On the other hand, it is important to note that the high penetration of PV systems has led to the consideration of future regulations following the path already written by the wind energy sector. In this way, future regulations about LV ride-through and reactive power compensation could be also applied to medium and large PV systems [24], [25]. This issue will become particularly important for large PV plants normally using conventional two-level, three-phase central inverters. Future regulations may force the power conversion stage to upgrade and motivate the introduction of more advanced multilevel converters and include energy storage to meet grid codes and provide the system operational flexibility.

B. Advances in DC-DC Converter for PV System

As was introduced in Figure 1, the dc– dc conversion stage is usually introduced to adapt the voltage range of the PV array to the dc bus of the PV inverter, and it simultaneously develops the MPPT control. Related to this issue, another topic of growing interest in the PV topologies has emerged in the field of module integrated converters (MICs). Generally, an MIC is a self-powered, high-efficiency, step-up dc–dc converter with galvanic isolation that operates with autonomous control and is integrated to the PV panel for tracking the maximum power point locally. The galvanic isolation is essential to reduce ground leakage currents and grid current total harmonic distortion [26]. As in the case of the previously mentioned PV inverters, the research trends here are directed toward the highest possible power conversion efficiency and power density. According to our research survey, the resonant power conversion with the maximum possible utilization of the parasitic elements of the circuit and the wide-bandgap semiconductors is the most popular approach for MIC performance improvement. Generally, MICs can be categorized as topologies either with a double- or single-stage power conversion. In the first case, the auxiliary boost converter steps up the varying voltage of the PV panel to a certain constant voltage level and supplies the input terminals of the isolated dc–dc converter. In that case, the primary inverter within the dc–dc converter operates with a near-constant duty cycle, thus ensuring better utilization of an isolation transformer.

In [27], the combination of a synchronous boost converter with a series resonant dc–dc converter (SRC) was presented [Figure 5(a)]. The SRC offers the advantages of high efficiency as it can operate without switching losses due to zero voltage switching (ZVS) and a high power density because of its bidirectional core excitation. The two stage structure could be simplified by the replacement of a boost converter with a passive impedance network [Figure 5(b)] [28]. The impedance network is a two-port passive circuit that consists of capacitors, inductors, and diodes in a special configuration.

A specific feature of the impedance network is that it can be short-circuited, which in turn, will lead to the voltage boost across the input terminals of the main converter [29]. Thus, the varying output voltage of the PV panel is first pre regulated by adjusting the shoot-through duty cycle (simultaneous conduction of both switches of the same phase leg of the inverter); afterward, the isolation transformer is being supplied a voltage of constant amplitude value. The impedance source dc–dc converter [30] extended by the series resonant network can minimize the switching frequency range of the traditional SRC and will lead to a high converter efficiency over a wide input voltage and load variation range. Moreover, because of inherent short-circuit immunity; the reliability can be enhanced substantially.

In a single-stage power converter, the primary inverter operates within the wide input voltage range and the efficiency optimization could become an issue. Here, different approaches were recently studied. For example, in [31], a highly efficient multi resonant dc–dc converter was proposed [Figure 5(c)]. Despite its complex structure, the converter has a minimal number of external discrete components in the design of the resonant tank: the series and parallel inductances are realized by using the leakage and magnetizing inductances of the isolation transformer, respectively. The parallel capacitance is mostly formed by the sum of the parasitic capacitances of the rectifying diodes and the isolation transformer. In this converter, the carefully optimized resonant tank leads to high efficiency within a wide specified input voltage range.

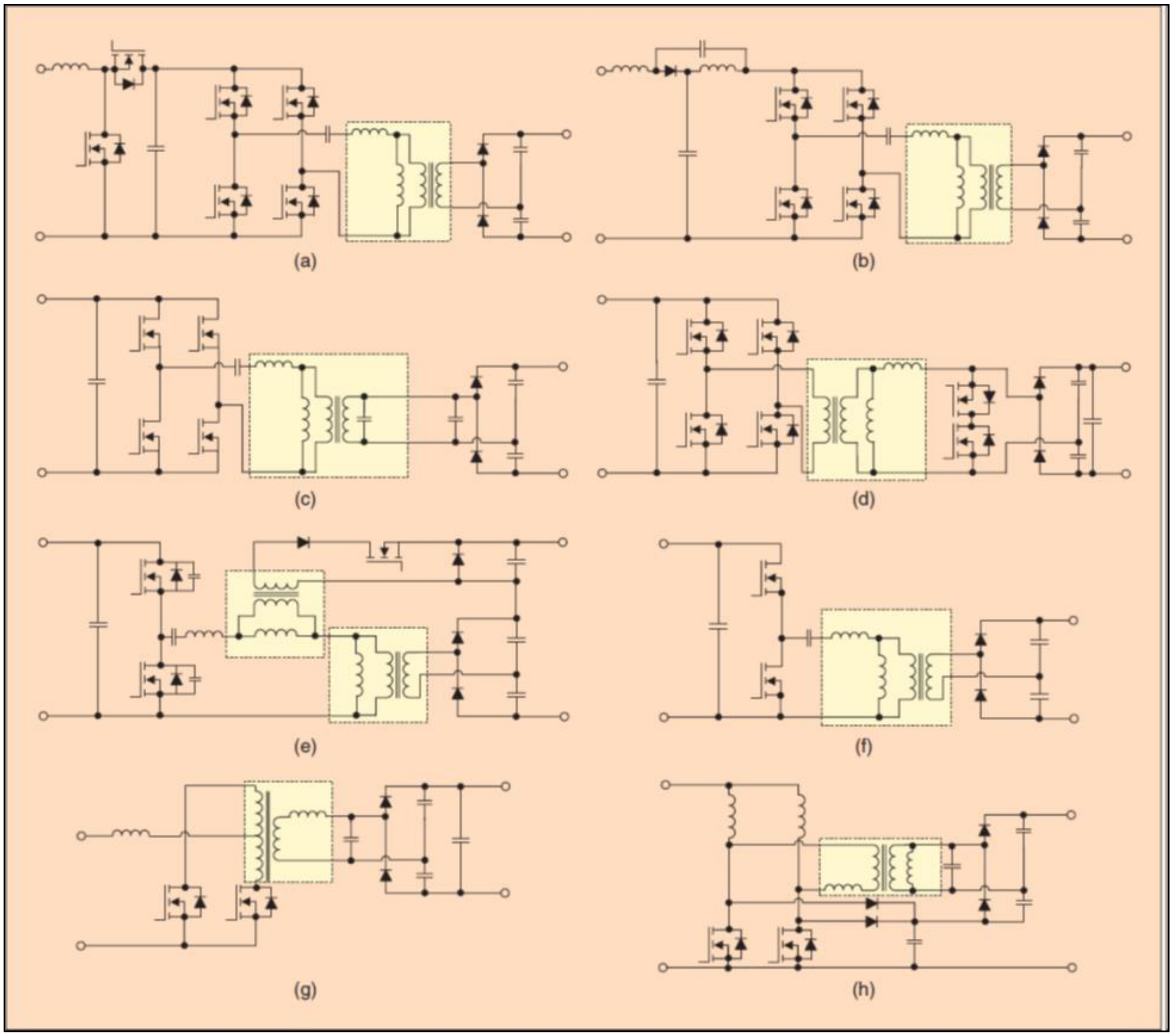

Fig. 5: The new emerged topologies of the PV module integrated dc–dc converters

The new resonant converter topology shown in Figure 5(e) can operate in two resonant modes adaptively depending on the panel operation conditions, thus maintaining a high efficiency within a wide input range at different output power levels [32]. As in the case of the previous topology, the specific properties of the circuit components, such as parasitic capacitances of

MOSFETs, leakage, and the magnetizing inductance of the transformers, were used as snubbers or elements of the resonant network. One of distinctive features of this novel topology is a half-wave rectifier added to the secondary side of the auxiliary transformer. When the half-wave rectifier is enabled, together with the voltage doubler rectifier of the main circuit, it will provide the output voltage0 equal to their summed output voltages.

The converter features ZVS for primary side switches and zeros current switching (ZCS) for rectifying diodes for both resonance modes and achieves the maximum efficiency close to 97%.

Another approach to the high-efficiency resonant converter for PV MIC applications is presented in Figure 5(d). With the simple addition of a bidirectional ac switch across the secondary winding of the isolation transformer, the highly efficient series resonant converter is combined with both a phase-shift modulated full-bridge buck converter and a pulse-width modulated boost converter to provide input voltage regulation over a wide input voltage and output power range [29]. The converter features the ZVS and/or ZCS of the primary side switches and the ZCS of the rectifying diodes, which finally results in a high efficiency within a wide operation range of the converter. In all of the previously mentioned dc–dc converter topologies, special attention was paid to the reduction of circulation energy to further increase the power conversion efficiency.

One of the significant advantages of the high-efficiency half-bridge LLC dc–dc converter [Figure 5(f)] is a reduced number of primary side switches and, therefore, a more simple structure than the previous MICs. As in the previous cases, the leakage and magnetizing inductances of the isolation transformer together with the external resonant capacitor form the LLC resonant network. As a result, the main power switches can achieve ZVS and the output diodes can realize ZCS in a wide input and load range [33]. Traditionally, with the help of the voltage doubler rectifier, the high voltage gain is realized with the optimal turn's ratio of the isolation transformer. The soft-switching current-fed push– pull converter presented in Figure 5(g) is another realization possibility of a simplified-structure MIC. [34]. It has the advantages of a traditional current fed push–pull converter, such as low input current stress, high voltage gain, and low conduction losses of switches.

Moreover, thanks to the parallel resonance between the secondary leakage inductance of the isolation transformer and a resonant capacitor, the transistors are turned on and off at the zero-voltage and zero-current conditions. The diodes of the voltage-doubler rectifier are also turned off at zero current. An interesting topology of the low-cost MIC was presented in [35]. The classical two-inductor isolated boost converter was further improved by use of a no dissipative regenerative snubber along with a hysteresis controller and constant duty cycle control [Figure 5(h)]. Furthermore, a multiresonant tank formed by the magnetizing inductance of the transformer, its leakage inductance, and the external resonant capacitor was introduced. As a result of all of these modifications, the proposed converter features a low input current ripple, ZCS conditions for the input switches and output rectifying diodes, and improved light-load behavior. Table 4 summarizes the most important specifications of the experimental prototypes of the discussed dc–dc converter topologies for PV applications. (It has an indicative character just to highlight the recent advances in the technology; more detailed information can be found in [29].

IV. CONCLUSION

The PV market has experienced exponential growth in the last decade, becoming an important alternative and a clean energy source in many countries.

Along with the decrease in price and the increase in efficiency of the PV modules, the PV converter topologies have been continuously changing, following more demanding requirements and standards.

These regulations are being adapted to a new power system scenario where renewable energy sources are an important part of the energy mix. Today, and meeting these legal requirements, PV converter topologies deal with issues such as high efficiency, high power density, and grid code compliance, reliability, long warranties, and economic costs.

A good number of PV converter topologies can be found on the market for string, multistring, central, and ac-module PV applications. Among all of these converter topologies, it can be affirmed that one of the most important appearances has been the multilevel converters, mainly the NPC, the T-type, and the H-bridge, not only for high-power applications but also for residential applications in the kilowatt and LV range.

In the near future, it is expected that a completely new family of PV converters will be developed based on SiC power semiconductors. (There are some commercial PV converters but only with SiC diodes.) These new SiC-based PV converters and the next-generation GaN PV converters will reduce the compromise between performance and efficiency, enabling the next generation of grid-connected PV systems.

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