Power Inverter Topologies for Solar Photovoltaic System

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Abstract: ***This review paper deals with the latest development of inverters for solar photovoltaic AC Modules. The power of the inverters ranges from 90 watts to 500 watts. This range covers most commercial PV modules. Self-commutated and also multilevel inverters (MLIs) have replaced the grid-commutated inverters. The same applies to the low-frequency and the high-frequency transformers, which are used for the adaptation of the voltage levels. AC Modules offer the advantage of modular design and flexibility. This leads to the market opening for photovoltaic power for everybody at low costs due to the plug-and-play concept and also the possibility of enlarging the system.***

Keywords: Topologies, Solar-photovoltaic system, Self-commutated inverters, Multi-level inverters (MLI); grid commutated inverters, AC Modules, design and flexibility, Plug- and- Play Concept.

1. Introduction

The inverter is necessary for two reasons. Firstly, the small DC voltage from the module has to be increased to a higher AC voltage in the grid. Secondly, the power taken from the module(s) is very dependent upon the point of operation, and the inverter has to be equipped with a function to track the Maximum Power Point (MPP). The most popular PV-technologies today are the single crystalline silicon and the multi-crystalline silicon module(s) [1]. The open circuit voltage of this kind of module lies in two ranges: either between 18 and 26 Volts for a 36 cells module, or between 38 and 46 Volts for a 72-cell module [2]. However, new technologies like the thin layer silicon, the amorphous silicon, and the Photo Electro Chemical (PEC) are in development. This implies that new modules, having just a single cell, could see the light of the day in the future. The voltage range of these cells/modules lies between 0.5 V and 2.0 V [3]. This paper begins with a historical overview. From the past, when a large area of several PV modules was interfaced to a centralized inverter, to the present, when a single or several modules are interfaced to a decentralized inverter, and then to the future, when the inverter would interface a single PV cell to the grid. Next, the overview of the existing power converter topologies for the AC module would be discussed. After the discussion of the multilevel inverter topology. These would be discussed to compare the topologies for future use, and then a conclusion would follow.

2. Evolution of Photovoltaic Inverters

A. The Past: Centralized Inverters

The past technology used a centralized inverter, which was connected to a number of modules. The modules are normally connected both in series, known as a string, and parallel to attain a high voltage and power level. This creates some limitations, such as the need for high voltage DC cables to connect the modules with the inverter, power losses caused by a centralized MPP tracking, mismatch between modules, and finally the string diodes. When one module in a string gets shaded, it will work as a load with reduced power generation. When the modules are connected in parallel, the shaded module will still be generating power, although the input voltage to the inverter will be reduced. A third option is proposed in [4] - [5], whereby each module has a generation control circuit. This will therefore ensure an individual MPP tracking for each module, which will reduce the chances of hot spots.

According to [6], the full shadowing of one PV cell (in a string of 160 cells) leads to an increase in the cell temperature of more than 70ºC compared with the ambient temperature, whereas the non-shadowed cells increase the temperature by only 22ºC compared with the ambient Temperature (in an ambient Temperature of 12ºC). This is of great importance, as an overheated cell quickly reduces the modules lifetime.

B. The Present: String Inverters and AC-Modules

The present technology, which is a hot research topic in Germany, is the ‘string-inverter’ [7]. String inverters use a single string of modules, to obtain a high input voltage of the inverter. However, the high DC voltage requires an unexamined electrician to perform the interconnections between the modules and the inverter. On the other hand, nooses are generated by the string diodes and an individual MPPT can be applied for each string. Yet, the risk of a hot-spot inside the string still remains. Another interesting solution is the ‘AC-Module’, where the ‘inverter’ is an integrated part of the ‘PV-module’ [5]. In this way, the losses due to a mismatch between modules and the ‘inverter’ are avoided, as well as the optimal adjustment between the two is facilitated.

The module and the inverter. Moreover, the hot spot risk is eliminated. All these, and a better efficiency can be achieved. It also includes the possibility of an easy enlargement of the system, due to the modular structure. The possibility of becoming a ‘plug and play’ device, which can be used by people without any education in electrical installations, is also an inherent part.

$$P_{grid}(t) = \hat{u}_{grid} \cdot i_{grid} \cdot sin^2 \cdot (\cdot\, \omega_{grid})PF \qquad (1)$$

$$P_{grid} = \frac{\hat{u}_{grid} \cdot i_{grid}}{2}\, PF \qquad (2)$$

C. The Future: AC-Modules and AC-Cells with MLI.
A solution for the future could be the AC Cell, which is the integration of one great PV-cell and the inverter [5]. The aim of these cells is to be an integrated part of the climatic barrier in buildings. The main challenge for the inverter is to amplify the cell's inherent very low voltage up to an appropriate level for the grid-connected inverter and, at the same time, to achieve high efficiency. The reason for that is the same, and entirely new converter technologies are required.

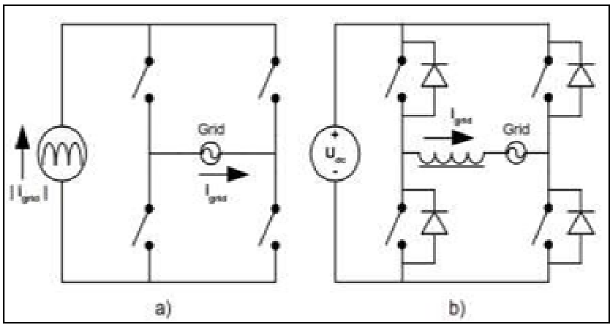

Figure 1: Grid-connected inverters: a) Current-fed, grid-commutated inverter switching at twice the grid frequency. b) Voltage-fed, self-commutated inverter switching at high frequency

The recent applications of MLIs include the fields of induction machine and motor drives, active rectifiers, filters, interface of renewable energy sources, flexible AC transmission systems (FACTS), and static compensators. The multilevel inverter topology is discussed in this paper.

3. AC-Module Topologies

The inverter used in PV applications must contain some essential functionalities. The conversion of this low voltage generated at the MPP (typically around 17 V for a 36-cell module and 34 V for a 72-cell module) to a corresponding AC current injected in the grid, must be done with the highest possible efficiency for a wide range of PV power. This requirement is given due to the irradiation distribution of the sun, as shown in Fig. 1 for a Danish Reference Year. Fig. 1 shows that most of the power is generated within the range from 200 W/m2 to 1000 W/m2 of irradiation.

The grid-connected stage in almost all the investigated solutions consists of a full bridge inverter towards the grid, either rid-commutated at twice the grid frequency [8] - [9] of Fig. 2a), or self-commutated with a high switching frequency [6]. The grid commutated operation is possible if the input current to the grid-connected stage is modulated to a rectified sinusoidal current. The benefits of this solution are that the switching losses of this stage are completely removed; this implies that the grid current must be sine modulated in another way, for example, by the DC-DC converter. On the other hand, the switching losses are, as a substitute, put onto the module-connected converter.

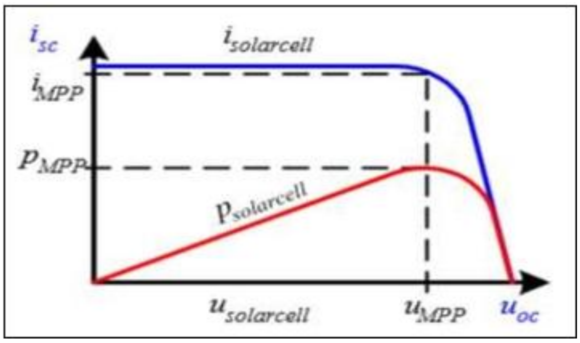

Figure 2: A Typical Current and power characteristic for PV-Cell or module

This is at the expense of a diminished power decoupling between the module and the grid, for the dual stage inverter, that makes it more difficult to remove the power fluctuations at the module. The fluctuation results from the penetration of the instantaneous low-frequency power flow to the grid, of (1). Another disadvantage is that both the module-connected the converter and the grid-connected inverter should be specified to operate at the peak power rather than the average power, which makes the design more complex and hence expensive. The peak power will be twice the average power, i.e., P_{peak} = 2 Pave, where $\hat{u}_{grid}$ and i_{grid} are the peak grid voltage and current, respectively; fgrid is the grid frequency; t is the time; and PF represents the power factor.

The transformer included inverters may use a low-frequency transformer or a high-frequency transformer. In the case of the low-frequency transformer, it has some drawback, e.g., the weight of the transformer, which should be attached to the module without making it mechanically fragile. Another drawback is the price, as this type of transformer should be manually mounted. In the case of modern inverters, the high-frequency transformer is used. In this case, new designs, e.g., the Printed Circuit Board integrated magnetic components, even without a core, may be used. However, the International Energy Agency-Photovoltaic Power Systems (IEA-PVPS), which is a task V [7], claims that the general requirement for the transformer included topologies is not valid, as the small amount of injected DC current into the grid does not affect the local distribution transformers. In the case of the inverter, the MPPT should be included to optimize the point of operation, where it generates the most power (U_{MPP} and I_{MPP}), of Fig. 2. Finally, the inverter must be low-cost but simultaneously it should have a lifetime around 25 years [2], which is the common lifetime for a PV-module. This calls for the use of more silicon devices, e.g. MOSFETs and IGBTs, which is still decreasing in price, at the expense of fewer capacitors and magnetic devices.

4. Single-Step Topologies for AC Modules

The single-step topology must include both the voltage amplification, the MPPT, the DC-AC inversion, and a power decoupling. All in one single inverter. It cannot be made without a transformer and simultaneously achieve a high efficiency, while the requested voltage amplification may reach almost 16 times for European grids. The topology presented here is the novel Bi-Directional Fly-Back (BDFB) inverter. Fig. 3. It is composed of two bi-directional fly-back converters, hence the name. The voltage-gain, A, is given by

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(3), in the case where the first converter is operated with a duty cycle equal to D, the second converter is operated with a duty cycle equal to (1-D), and the currents through the transformers are continuous

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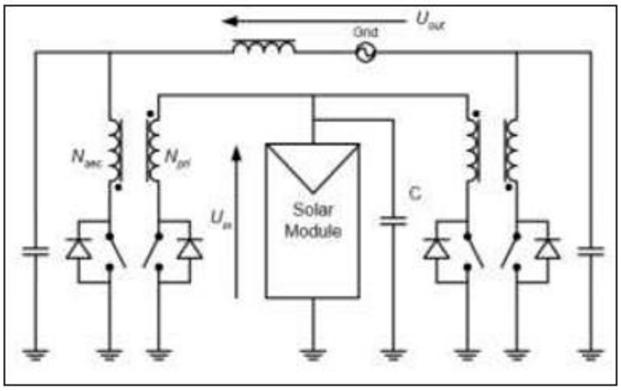

Figure 3: A novel single-step solution for an AC Module: Bidirectional Fly Back Converter

$$K = \frac{U_{out}}{U_{in}} = \frac{N_{sec}}{N_{pri}} \cdot \frac{2 \cdot D - 1}{D^2 - D}, \quad (3)$$

where N_{sec} and N_{pri} are the secondary and primary turns numbers. U_{in} is the module voltage, and U_{out} is the voltage across the grid and the grid-connected inductor. The converter is able to operate under the Continuous Conduction Mode (CCM) at any time due to the bi-directional current flow capability. The amount of power ripple at 100 Hz may be substantial compared to the amount of power ripple found with the dual- and multiple-stage inverters. A solution to remove the power ripple is the use of the input capacitor, as shown in. C is the required capacitor at the front of the module to attain a power ratio defined as: PPV, AVG / PMPP = k, where PPV, AVG is the average power delivered from the module, PMPP is the power at the MPP, ω_{grid} is the grid frequency, and U_{MPP} is the maximum power point voltage. For example, the MPP voltage is 34.0 V, corresponding to a 72-cell PV module. In addition, k = 0.99 and the capacitance value is required for the European market, which is as high as 14 µF/W. This is substantial compared to the dual- or multiple-step solution, where the DC-link capacitance is equal:

$$C \approx \frac{P_{MPP}}{2 \cdot \omega_{grid} \cdot U_{MPP} 2\sqrt{1-K}}, \quad for\ k \approx 1 \quad (4)$$

$$C \approx \frac{P_{grid}}{2 \cdot \omega_{grid} \cdot U_{dc} \cdot \tilde{u}_{dc}}, \quad (5)$$

where $P_{grid}$is the power delivered to the grid,U_{dc} is the average DC-link voltage and $\tilde{u}_{dc}$ is the amplitude of the small-signal DC-link voltage Again for the European case, with an average DC-link voltage of 360 V and a small-signal amplitude of 20 V, this gives us 220 nF/W. A prototype of the 'Variable Output Bidirectional DC-DC Converter' is tested in [30]. The following specifications were used: U_{in} = 165 V, U_{out} = 0 V to 250 V, P_{out} = 1 kW, and fswitch = 100 kHz.

The specifications of the transformer used were:
$N_{pri} = N_{sec}$ with a magnetizing inductance of 100 µH. The converter is used to drive a piezo-ceramic actuator with a working frequency range from zero to 500 Hz. Note that the switching frequency is still 100 kHz.

Another way is to use a standard full-bridge inverter with a bulky 50 Hz transformer. However, this is not a good solution since it uses a bulky transformer and does not have power decoupling between the module and the grid.

5. Multi-Step Topologies for AC-Module

The high number of steps (or stages) involved makes the complexity and cost of the multi-step topology higher than the one- or two-step solutions proposed earlier. However, it will be possible to use a 100 Hz inverter with a corresponding rectified sine modulated DC-DC converter and still achieve a power decoupling between the module and the grid. This will lead to low switching losses for the grid-connected stage and good MPPT properties.

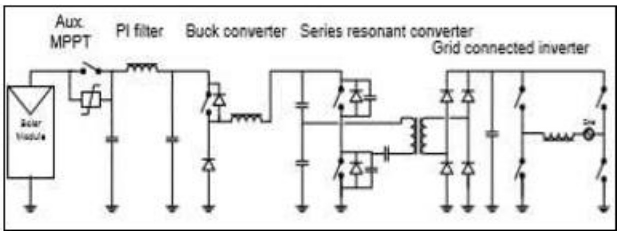

Figure 4: Schematic for multistep topology

The last commercial inverter for the AC-Module inverter under consideration is the Sun master 130S [9], see Fig. 4. This inverter is radically different from the ones just considered. First of all, it has an auxiliary MPPT circuit, and secondly, it has three stages. The inverter connected to the grid operates at 100 Hz, which again means that the stages are not decoupled. The second stage is a series resonant converter with a high-frequency transformer and rectifier. The resonant tank consists of a resonant capacitor, the transformer, and the resonant inductor, which is part of the leakage inductance of the transformer.

This stage is referred to as a 'DC-transformer', i.e. it is operating with a constant duty cycle smaller than 50% and with a constant frequency, i.e. without control. The module-connected converter is based on the buck converter with the output current modulated in accordance with the well-known rectified sine current. The amplitude of the sinusoidal current is modulated in accordance with the MPPT.

The insertion of the pi-filter, owing to the auxiliary MPPT circuit, is between the buck converter and the MPPT circuit. The PV module is disconnected in 200 µs every two seconds. The stepdown converter is then connected to the input capacitor, and the MPP voltage is derived from the module's open circuit voltage, U_{OC}, as follows:U_{MPP}= 0.8 U_{OC}. This is a fast and simple way of realising the MPPT as long as the modules are well characterized. If the modules change, e.g. as a function of temperature, then it is not possible to track the MPP with a reduced power as a consequence.

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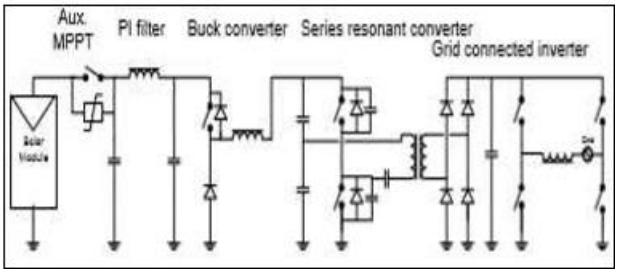

Figure 5: The proposed topology for the grid-connected inverter unfolds the rectified-sine current generated by the push-pull converter

The next inverter is presented in the paper [10] and is shown in Fig. 5. A boost converter is used to boost the module voltage to 200 V DC and to track the MPP. In addition, it is used to supply the auxiliary circuits. This is accomplished via a secondary winding of the boost inductor and a matching rectifier. A push-pull converter is used to ensure galvanic isolation between the module and the grid. In addition, it is used to control the grid current and the 100 Hz full-bridge inverter is used to unfold the rectified sine current, which is generated by the push-pull converter. A prototype of this type of inverter is presented in the paper [10]. The parameters of this prototype are as follows: U_{in} = 30 V...170 V, P_{in} = 500 W. Efficiency is better than 70 % at an input voltage of Uin = 45 V and power higher than 90 W. Such low efficiency is caused by the boost converter. It is not surprising, as the boost converter is used to boost the voltage of the PV module from 45 V to 200 V DC, or 4.44 times.

Fig. 4 shows a schematic for a multistep topology. It consists of the buck converter, which modulates the sinusoidal current. The series resonant converter acts as a 'DC-Transformer', and the grid-connected inverter unfolds the current. Fig. 8. This figure shows that the proposed topology in [10] is used. The grid-connected inverter unfolds the current from the 'Rectified Sine' current generated by the 'Push-Pull Converter'. The 'Boost Converter' is used for MPPT. The 'PV-Module' current, and hence voltage, is kept constant by using a 'Boost Converter' in front of the 'PV-Module', which will work as a constant current load. In this way, the module, together with the grid, will be power decoupled. The auxiliary winding of the boost inductor will be used for the Auxiliary Power Supply Unit (APSU).

The efficiency of the boost converter has been measured to be approximately 80 % for 90 W of output power. The efficiency of the grid-connected inverter will always be above 99 %; however, in the case of the thyristor-equipped inverter, only two times the diode forward voltage drops, together with the absolute average grid current, will be responsible for the losses.

6. Multi-Level Inverter Topology

The recent trends of MLIs are quite diverse, ranging from induction machine and motor drives to active rectifiers, filters, renewable energy sources, flexible AC transmission systems (FACTS), and static compensators. The diode clamped inverters, particularly the three-level structure, are quite popular for motor drive applications besides other multi-level inverter topologies. MLIs have a variety ranging from induction machine and motor drives to active rectifiers, filters, renewable energy sources, flexible AC transmission systems (FACTS), and static compensators.

The multi-level inverters [12] are gaining much attention for medium voltage and high-power application areas due to their numerous advantages, such as reduced common mode voltage, reduced voltage stress on power switches, reduced dv/dt ratio to supply lower harmonic contents in output voltage and current. The diode clamped inverters, particularly the three-level structure, are quite popular for motor drive applications besides other multi-level inverter topologies.

The most common MLI topologies [11] classified into three types are:
1) Diode clamped MLI (DCMLI),
2) Flying capacitor MLI (FC-MLI),
3) Cascaded H-Bridge MLI (CHB-MLI),
4) Hybrid MLI.

The hybrid and asymmetrical hybrid inverter topologies have been developed based on the combination of existing multilevel inverter topologies or based on the different DC bus levels, respectively. However, this may be considered as a limitation of the complexity and the number of the clamping diodes of the DC-MLIs for levels higher than three. The FC-MLIs are based on the balancing capacitors of the phase buses and generate the multilevel output voltage waveform that is clamped by the capacitors rather than the diodes. The FC-MLI topology requires the balancing capacitors per phase of the level (m-1) *(m-2)/2 for the multilevel inverter and will cause an increase in the number of capacitors required for the high-level inverter topologies. Among the three types of multilevel inverters, the cascade inverter has the least components for a given level.

Apart from the above-mentioned types of MLI, the Cascade Multilevel inverter is one of the types of multilevel inverters that is very suitable for solar grid integration applications. There are various modulation and control techniques used for controlling multilevel inverters. Some of them are selective harmonic elimination pulse width modulation (SHE-PWM), sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVM), etc. The SPWM control method is very popular in industry because it offers a great opportunity to reduce harmonics by using a number of phase shift options in the carrier signal. Cascade multilevel inverter consists of a number of H-bridge cells to produce a required voltage from a number of separate DC sources (SDCSs), which are obtained from batteries or fuel cells. All these characteristics of cascade inverters allow using various pulse width modulation (PWM) techniques to control the inverter accurately. Hence, the cascade H Bridge multi-level inverter is the most suitable for renewable energy applications.

7. Conclusion

This review has covered a few different inverter topologies for photovoltaic applications, as well as particular inverters for the AC Module. From the topologies of single-stage as well as multistage inverters, it has been found that the Bi-Directional Fly-Back Inverter as well as resonant inverters are more promising topologies. However, it is necessary to take some measures to reduce the power coupling between the module as well as the grid by means of the Bi- Directional Fly-Back Inverter topology. Moreover, it is necessary to perform some research work to check whether the Bi- Directional Fly-Back Inverter topology is worthwhile to use two high-frequency transformers. In this paper, it has been considered that the AC Module is a solution for the future. Hence, the next step in the development phase of an inverter for an AC Module is to specify some specifications for the inverter. These specifications must be mentioned, considering the availability of photovoltaic modules as well as the grid performance. A simplified single-phase multilevel inverter is proposed for solar grid integration applications. And it is compared with the conventional single-phase cascaded H-bridge topology. So, SPWM topology is a very simple control strategy.

References

[1] J. P. Benner, L. Kazmerski, “Photovoltaics gaining greater visibility”, IEEE Spectrum, vol. 29, issue 9, pp. 34-42, September 1999.

[2] S. B. Kjær, State of the art analysis for the ‘Solar cell Inverter’ project, Aalborg University, 2001, unpublished.

[3] M. Wuest, P. Toggweiler, J. Riatsch, “Single cell converter system (SCCS)”, IEEE proc. of 1st WCPEC, vol. 1, pp. 813-815, Dec. 1994, USA.

[4] T. Shimizu, M. Hirakata, T. Kamezawa, H. Watanabe, “Generation control circuit for photovoltaic modules”, IEEE trans. on power electronics, vol. 16, no. 3, pp. 293-300, May 2001.

[5] M. Calais, V. G. Agelidis, “Multilevel converters for single-phase grid-connected photovoltaic systems – an overview”, IEEE proc. of ISIE’98, vol. 1, pp. 224-229, July 1998, South Africa.

[6] P. Rooij, M. Real, U. Moschella, T. Sample, M. Kardolus, “Advanced reliability improvement of AC-modules (ARIA)”, Netherlands energy research foundation ECN, Contract: JOR3CT97-0122, May 2000.

[7] B. Verhoeven, et. al. Utility aspects of grid-connected photovoltaic power systems, International Energy Agency PVPS task V, 1998.

[8] S. W. H. de Haan, H. Olden Kamp, E. J. Wilden Beest, “Test results of a 130 W AC module; a modular solar ac power station”, IEEE Proc. of 1st WCPEC, pp. 925-928, December 1994, USA.

[9] S. Saha, V. P. Sundar Singh, “Novel grid-connected photovoltaic inverter”, IEE proc. of Generation, Transmission and Distribution, vol. 143, issue. 2, pp. 219-224, March 1996.

[10] U. Herrmann, H. G. Langer, H. van der Broeck, “Low cost dc to ac converter for photovoltaic power conversion in residential applications”, IEEE Proc. of 24th PESC, pp. 588-594, June 1993, USA.

[11] Bailu Xiao, Faete Filho, Leon M. Tolbert, “Single-Phase Cascaded H-Bridge Multilevel Inverter with Non-Active Power Compensation for Grid-Connected Photovoltaic Generators,” *IEEE Trans. Ind. Elec. 2013.*