POWER CONVERTERS FOR PHOTOVOLTAIC GENERATION SYSTEMS IN SMART GRID APPLICATIONS

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***Abstract* – This paper presents an overview of the power converters that are adopted in PhotoVoltaic generation systems in the power range till 20 kW. For this type of renewable energy applications a double trend can be identified according to power conversion systems below few kW and higher than 3-5 kW. The paper deeply analyses both converter configurations also taking into consideration the control aspects connected to the efficient and reliable connection to the grid of such systems. Some experimental results are presented dealing with two prototypes belonging to each of the identified classes of converters.**

***Keywords* – Converter Topologies, PV String Conversion, PV Panel Converters, Grid Connection**

I. INTRODUCTION

Almost completely, the requisites that make effective any reduction of energy consumption and CO2 emissions are based on Power Electronics. Stabilization of the power grids with slow and constant integration of fluctuating renewable energies, effective and efficient injection of wind and solar energy into the grids, use of efficient controlled speed motor drives in industry and transportation, adoption of full electric or hybrid vehicles to allow energy efficient and low emission mobility, achievement of large scale energy savings in home appliance and lighting technologies, efficient energy recovery and energy management of storage systems, all such results can only be obtained through an extensive application of Power Electronics. The strategic and ambitious goals of the European Union for 2020 depend on the Europe's political choice and technical capability to provide a real adoption of the multidisciplinary techniques and components that are included in Power Electronics.

In a recent presentation of the ECPE (European Consortium on Power Electronics) Research Roadmap Team on "Power Grid Infrastructure & Renewable Energy Sources", integration of different renewable energies has been indicated as one of the strategic tools to achieve the goal of having the Renewables (Wind and Solar) to contribute up to 30% to the global electricity energy production in 2030. By adding the contribution from hydro power, mainly produced in North-East Europe, the situation depicted in Figure 1 is predicted, where Solar thermal and Photovoltaic (PV) power generation coming from South Mediterranean countries can contribute either with large scale PV installations and solar thermal plants either with distributed small scale PV plants. Integration to the grid of the renewable energies will occur via HVDC, energy lines with UHVAC and UHVDC, and in case of low voltage networks via distributed intelligent PV

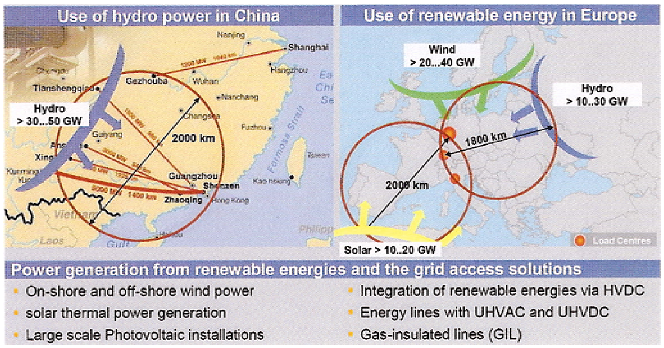

Fig. 1. Grid access for large scale renewables (Source: Siemens AG).

converters and advanced PLC. Intelligent Super Grid and Smart Grids interconnected as in Figure 2 are foreseen as the future energy systems [1].

In this scenario, while Power Electronics will have to face important challenges such as those of supplying high power Voltage Source Control technology, DC-circuit breakers for meshed HVDC overlay grids, improved DC-grids, and MV DC/DC converters with or without galvanic isolation, power converters for low-power PV generation systems will also cover an increasing important role as they appear the only tool to effectively establish large scale distributed energy, generated by the sun and connected to the grid. In fact, even in the future distributed generation systems exploiting sun energy will continue to be based on a conversion process where power converters, advanced Pulse Width Modulation (PWM) techniques, and microcontroller based control systems are associated to achieve high conversion efficiency, high power factor, and low current harmonic THD [2].

Nowadays, technical improvements and advances in the circuit design of the converters, and integration of the required control and protection functions into the converter control circuit have allowed to introduce into the market advanced PV converter systems that also provide sufficient control and protection functions such as maximum power tracking, inverter current control, and power factor control. Within the range of power till 10 kW several DC/AC converter configurations have been proposed from single stage to double or multi-stage topologies according to the number of cascaded power stages, with or without a low or high frequency power transformer.

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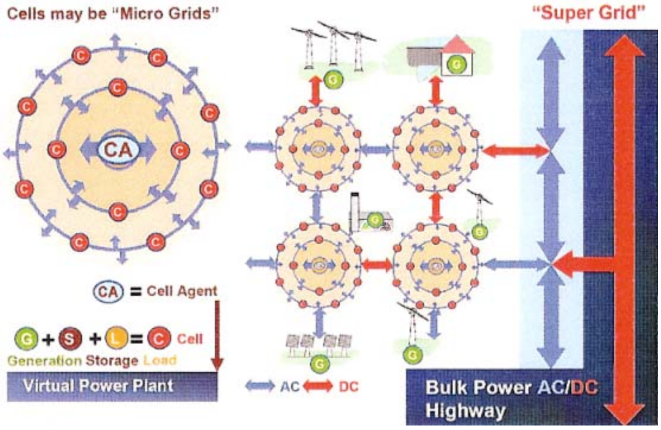

Fig. 2. Future energy system will be formed by intelligent Super Grid and Smart Grids (Source: Siemens AG).

Single-stage single-phase or three-phase inverters are the traditional solution adopted to interface a large number of PV modules to the grid as the modules are connected in series to create strings with a suitable high value of the output voltage and the strings are connected in parallel through interconnection diodes to obtain the desired power level. The presence of the low-frequency transformer and the poor efficiency of the centralized inverter associated to the poor performance of the Maximum Power Point Tracker (MPPT), have moved to "string conversion" solutions, which basically consist in a double stage power converter for each string of the PV plant. Using an input stage in boost configuration allows one to connect less panels in series to create the DC voltage, while increasing the overall efficiency of the power conversion, as the blocking diodes are not requested and the MPPT algorithm is applied to only one string with limited number of panels. String conversion configurations based on several DC/DC converters connected to a high voltage DC bus and linked to a single DC/AC converter in principle appear as more complex solutions but offer higher efficiency due to single string MPPT control and modularity of the PV plant. Finally, for very low-power applications it is recognized that the solution based on AC modules is the best one to solve such issues as input power optimization, plant modularity, and system reliability. With this architecture every single PV panel is directly connected to the grid through MICroinverters (MIC) having the same power of the panel and installed on its backside.

This paper will present the most updated solutions that use multiple power converters for string and panel conversion, aiming to demonstrate how the recent developments of power electronics can help to overcome such issues as cost, efficiency, and reliability that still limit wide-spread adoption of low-power PV generation systems.

II. DC/AC CONVERTERS FOR STRING CONFIGURATION

In Europe, since the grid is operated with a nominal voltage of 230 Vrms at the single-phase stage, the power converter must perform two tasks: the PV array DC voltage level must be adjusted by buck or boost operation of the DC/DC unit and then converted into AC through the DC/AC stage. In addition, the power converter should provide galvanic isolation between the PV array terminals and the utility grid for safety issues. In the past, these tasks were performed by connecting an inverter followed by a 50 Hz transformer to the PV field. Nowadays, for low power applications, a DC/DC converter is preferred in order to limit physical size and cost of the system. Mainly, the DC/DC unit can be a current source or a voltage source converter. A current source DC/DC converter requires less capacitive filtering since the input inductor smoothes the high frequency current ripple. For this reason, most manufacturers use current source isolated or non-isolated DC/DC converters. With proper design, all the state of the art topologies can lead to high efficiency operation. The most used ones are the full-bridge boost, push-pull, and non-isolated boost converters. At the same time, they are well known technologies and have good utilization of magnetic components and power switches. The two most attractive single-phase DC/AC inverter topologies are the Full-Bridge (FB) and half-bridge configuration. A standard FB inverter is preferred due to better exploitation of the materials and high efficiency capability (Figures 3, 4).

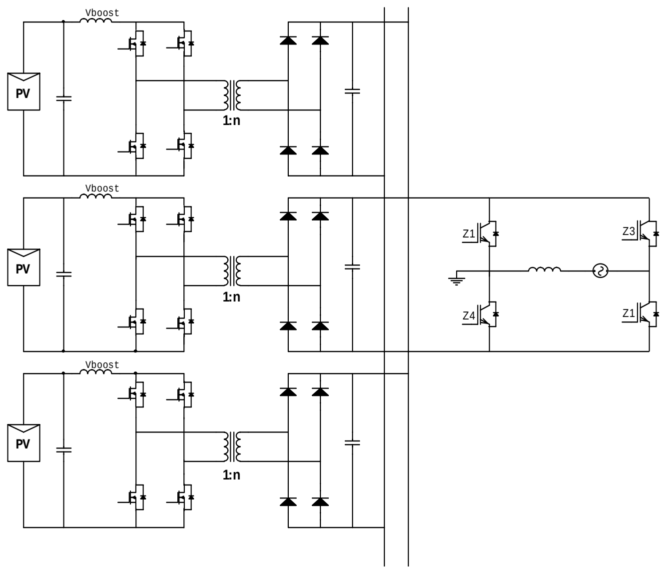

Fig. 3. Multi-string/multi-stage converter (DC/DC boost Full-Bridge and Full Bridge inverter).

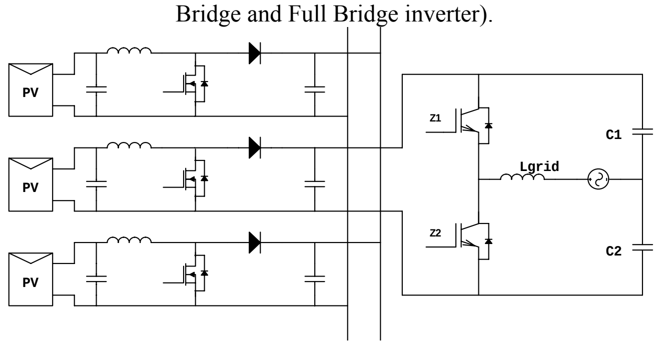

Fig. 4. Multi-string/multi-stage converter (DC/DC boost and half bridge inverter).

In conventional topologies, as the DC bus includes electrolytic capacitors, which are bulky, heavy and suffering from degradation especially caused by temperature effects, the DC link is the prime factor of reliability degradation of the power conditioning system. By replacing electrolytic with the new film capacitors, a relevant source of failure can be eliminated. As a result, an increase in lifetime and reliability of the power converter can be achieved at the price of added cost. Reliability can be further improved by a modular design approach. For instance, the already mentioned connection of two or more DC/DC modules to a common DC bus and the use of a single DC/AC unit can be advantageous in terms of reliability, efficiency, PV array configuration and maximum energy yield. Such a system can be managed by means of a central microcontroller, providing the inverter PWM control for grid connection operation and supervision of each microcontroller unit equipping a DC/DC module. In large PV plants the central controller unit can also select the operation of an optimized number of modules according to irradiation levels. Market and advanced converters for grid-connected PV systems can be analyzed to check their operation according to such standpoints as efficiency, easy design, quality of the generated voltage, best exploitation of the performance of the solar source, best design of the power buffer, and compliance with the international standards in terms of power quality and electromagnetic compatibility. An example of such a comparison is reported in Table 1 and concerns with three popular PV converters available on the market for a power around 3 kW.

TABLE 1
Commercial Converter Specifications

	Power			Topologies		Dimensions		Cost	
	Rated DC Input [W]	Max DC Input [W]	Max AC Output [W]	Isolation Transformer	Multi-string Capability	Size/Weight [mm]/[kg]	Power Density	Total	€/kW
1	2.500	3.600	2.650	HF Trafo	no	366x338x220 9	97,4 [W/litre] 294,4 [W/kg]	€1.940	€732
2	4.000	not declared	3.600	TL	yes	420x326x141 13	186,5 [W/litre] 276,9 [W/kg]	€3.462	€962
3	4.200	4.400	4.200	TL	yes	470x490x225 31	81,1 [W/litre] 135,5 [W/kg]	€3.928	€935

III. ADVANCED DC/AC CONVERTERS FOR STRING CONFIGURATION

Despite of the continuous improvements in the design and manufacturing of power semiconductor devices, hard switching converters still suffer from high switching loss and severe EMI due to high $\frac{di}{dt}$ and $\frac{dV}{dt}$.

Soft switching techniques, which can shape the rising and falling edges of switch current and voltage waveforms of the conventional PWM are the solution to eliminate those drawbacks. At the same time, switches and diodes can be turned on or off under zero voltage and/or current, meaning minimal switching loss. Zero voltage transition (ZVT) and Zero Current Transition (ZCT) are two classes of the most practical soft switching techniques available for power converters. In the last few years, different ZVT and ZCT converters have been proposed [3], not only with the aim of minimizing the switching loss to improve the efficiency, but also to achieve high performance in terms of wide control bandwidth, high power density, and low THD which are issues directly connected to the high switching frequency. Another advantage is the absence of parasitic effects due to the HF transformer leakage inductance. As a consequence, snubber circuits can be omitted or drastically reduced with good overall cost reduction and component number minimization.

A recently proposed converter scheme [4] is shown in Figure 5. The general specifications of the converter are identified in Table 2 and have been calculated according to the considerations that efficiency maximization is easily achieved in a power converter operating with high input voltage and low input current due to sensible reduction of conduction losses. Moreover, for a 3 kW string inverter with an average efficiency of 90% the input voltage can be as high as 600V (in open circuit condition) and, as in this case, it can vary between 370 and 450 V according to both the maximum power point of operation and power ratings of commercial PV modules. Finally, the switching frequency is a trade off between efficiency, size, and cost of the converter. For example, the DC/DC converter switching frequency was set at 35kHz as an efficiency compromise to take into account the limited range of ZVS operation with input voltage levels different than 300V. In those operating conditions, higher switching frequencies would cause unwanted additional losses due to hard switching.

TABLE 2
Main Converter Specifications

Maximum Input Voltage	V_{in_max}	400 V
Output Voltage	V_{grid}	230 V
DC Bus Voltage	V_{bus}	450 V
MPPT Range	V_{MPPT}	370 – 450 V
DC/DC Switching Frequency	f_S	35 kHz
Output Power	P_o	3,0 kW

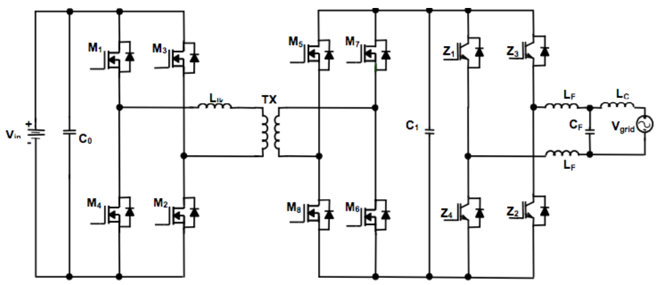

Fig. 5. DC/AC Converter including ZVS Full Bridge phase-shift DC/DC and Full Bridge DC/AC.

As a result of power loss calculation and voltage and current ratings, at the design stage of the converter 47A, 650V Power MosFET devices were selected for the DC/DC converter featuring 60mΩ R_{dsON}, and 30A, 600V IGBTs were adopted for the DC/AC stage implementation. Each device in the DC/DC stage is connected in parallel to a fast soft recovery diode. The choice of such MOSFETs featuring low R_{dsON} and gate charge as well as diode characteristics is a critical aspect in case high efficiency is demanded. As it is shown in Figure 6, the converter efficiency is higher than the market PV converters at different input voltages and almost constant in the whole power range. In addition to conversion efficiency, control optimization of the DC/AC converter is still quite an open challenge in case of single-phase, grid-connected distributed generation systems. High performance requested by international standards in stringent terms of current distortion, power factor, and anti-islanding protection impose that sophisticated algorithms must be employed involving complex mathematical operations and multiple PWM outputs for driver signal generation. Therefore, high computational resources are required but only recently it has been demonstrated that they can be reduced to those of standard microcontrollers. For example, the control board of the converter shown in Figure 5 is equipped with a microprocessor based on a 32 bit CORTEX™-M3 core with suitable peripherals. The core, running at 72MHz, is able to perform up to 90 MIPS while a high performance CPU, plus suitable peripherals such as advanced PWM, fast and accurate A/D conversions (12 bit with double S&H circuit) and high resolution timers, are used. All PWMs are generated with proper dead time, set by software with few nanoseconds of resolution.

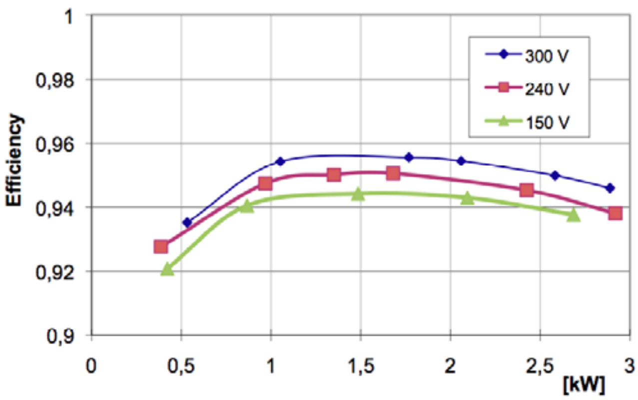

Fig. 6. Measured Efficiency of the DC/AC Converter.

The control strategy adopted for grid connection of the converter is based on the control of the active and reactive power in the d-q axis reference frame synchronous with the grid voltage vector [5]. The grid angle is estimated through an advanced PLL implemented in the same d-q reference frame, in order to achieve wider bandwidth, lower noise sensitivity, and higher accuracy compared to a standard PLL. The MPPT algorithm is implemented as an optimized version of the Perturb&Observe method [6].

IV. DC/AC CONVERTERS FOR PV PANELS

Although the design techniques of converters for PV panels may change according to the panel specifications, efficiency and voltage gain are the two most important performance required to such architectures. In particular, a high voltage gain of the DC/DC converter is requested and this can be obtained through charge-pump systems or high-frequency transformers, that remain the best choice in case galvanic isolation is required.

In Table 3 are reported the results of performance comparison of six DC/DC converters chosen among the most adopted solutions. Efficiency of each configuration has been calculated through application of the "Californian Ponderation" expression:

$$\eta_{CEC} = 0,04*\eta_{10\%} + 0,05*\eta_{20\%} + 0,12*\eta_{30\%} + 0,21*\eta_{50\%} + 0,53*\eta_{75\%} + 0,05*\eta_{100\%} \quad (1)$$

TABLE 3
Comparison of Converters for PV Panels

Converter Performance	Classic Transf	Dual Boost	L-Type	Multi Stage	Multi Cell	Flyback
Efficiency	95%	90%	92%	95%	97%	93%
Switch	2	4	4	2	2	1
Max V Stress	V_{out}/n	$V_{out}/2$	$V_{out}/2$	$V_{out}/4$	$V_{out}/4$	V_{out}/n
Max I Stress	In/2	In/2	In/2	3In/4	3In/4	In
Diode	2	2	2	4	10	1
V Stress on Diode	2 V_{out}	2 V_{out}	2 V_{out}	$V_{out}/4$	$V_{out}/4$	2 V_{out}
I Stress on Diode	In/2n	3In/4	3In/4	3In/4	3In/4	In/2n
Transformer	Si	Si	SI	Auto + NS	Auto	Si

that more precisely takes into account the operating conditions of PV systems in hot temperature regions. Common simulation tools have been used such as PSIM and SPICE and it has been assumed that the same type of transistor is used in all converters. The six converters belong to different classes of configurations starting from the classic interleaved boost with HF transformer that ensures high voltage gain (Figure 7). The switch control strategy is a standard interleaved PWM between the two channels, able to reduce the ripple of the input current, as the two transistors have the same switching frequency and duty-cycle and a phase shift of 180°. In Figure 8 is shown the Dual Boost-Interleaved converter that uses two HF transformers to charge the output capacities and again ensure the high voltage gain. In this case two interleaved phases are introduced with two transistors each that are driven according to the shown strategy where a small overlapping is inserted in the 180° phase shift. According to Table 3 the two isolated boost converters have in high voltage gains and low voltage stress on the transistors their best performance, while especially the Dual Boost is penalized by the number of devices and voltage and current stress. Efficiency of Dual Boost (90%) is also lower than that shown by the classic Boost-Interleaved (95%).

An alternative interleaved isolated boost converter is the L-type half-bridge shown in Figure 9. In this case the two transformers have no central connection in the secondary winding but they still allow one to shift of 180° the secondary voltages according to the shown configuration and, most important, through the circuits obtained with the four diodes the charge of both output capacitors is contributed by both transformers. Efficiency is in between the two previous converters but number of switches and diodes, and stress is the worst as always in this class of converters.

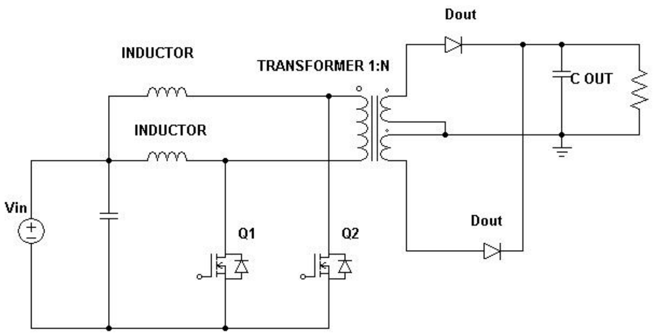

Fig. 7. Boost-Interleaved Converter with HF Transformer.

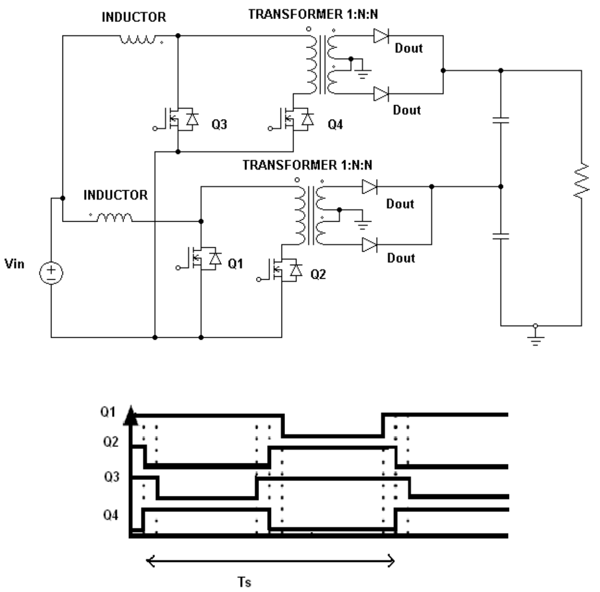

Fig. 8. Dual Boost-Interleaved converter with HF Transformers.

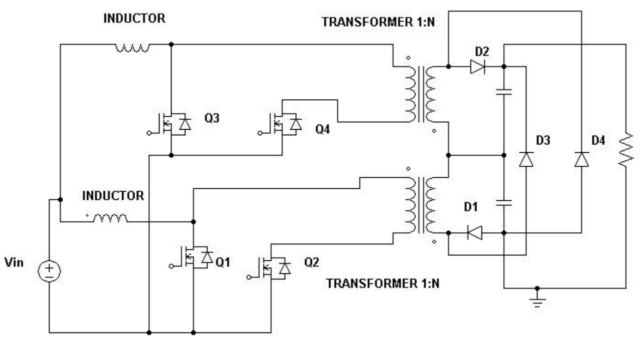

Fig. 9. L-type Half-Bridge Interleaved Isolated Boost converter.

As it has been proved by the simulation comparison, in order to increase the converter efficiency Multi-stage or Multi-cell configurations have to be adopted. The Multi-stage converter of Figure 10 is still an interleaved two-phase boost with the peculiar characteristic of using a single inductor and a transformer with two primaries and a secondary winding. The two transformer primaries are fed by 180°-shifted voltages in order to reduce the current ripple and make equal the phase currents. The secondary winding charges a voltage doubler, which is connected to the positive terminal of the output capacitor of the interleaved boost.

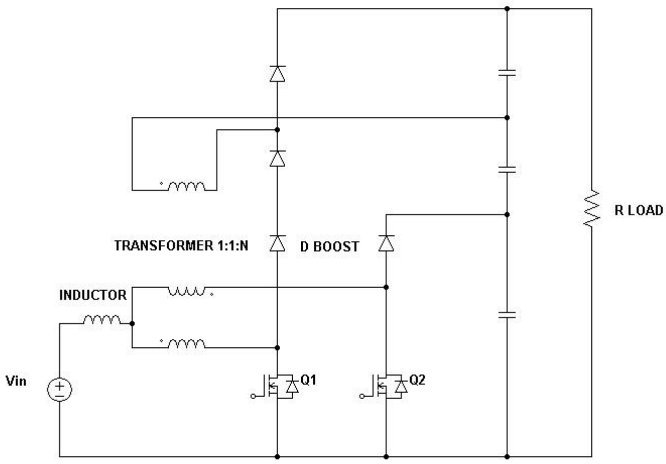

Fig. 10. Multi-stage converter.

The Multi-cell converter of Figure 11 is also based on an interleaved boost with coupled inductors to reduce the ripple of the input current. However, in this case a charge-pump system including diodes and capacitors is added to the two transistors. This converter is highly penalized by the number of diodes although each one of them experiences a voltage stress eight times less than the other topologies and a voltage stress on the transistors that is half of the dual boost and L-type boost.

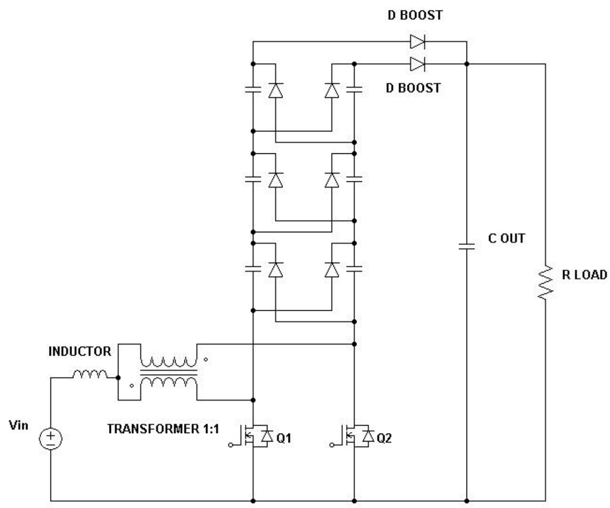

Fig. 11. 3-Stades Multi-cell converter.

Finally, in Figure 12 is shown a MiCroinverter based on a cascade connection of flyback and inverter stages. Such a configuration is advantaged on other topologies as it has no need of a stage with high frequency inverter to reconstruct the current sinusoidal wave. The first stage of this MIC produces a sinusoidal rectified current and also represents a fictitious load to the PV panel in order to force the system to operate at the maximum power point. The second stage which is aimed to grid connection, acts inverting the output current of the first stage every half a cycle of the grid voltage. The Full Bridge switches are operated at a double frequency than that of the grid thus obtaining two advantages: a dramatic reduction of the inverter switching losses and the possibility to use low frequency IGBTs with very low voltage drop (low V_{CEsat}).As it shows the higher efficiency and best performance at low and high loads, the Multi-cell converter seems the best candidate to cover a worldwide market request of MICs including bus multivoltage feature for European (230 V) or North America (110 V) requirements. In Figure 13 the efficiency curve calculated at different loads on an experimental prototype confirms the simulation predictions.

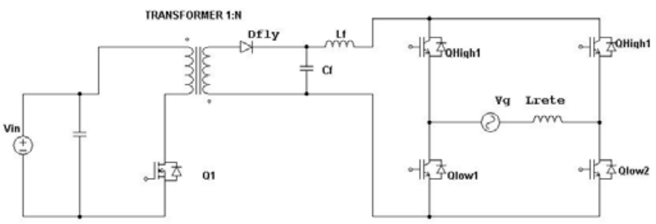

Fig. 12. Flyback MICroinverter

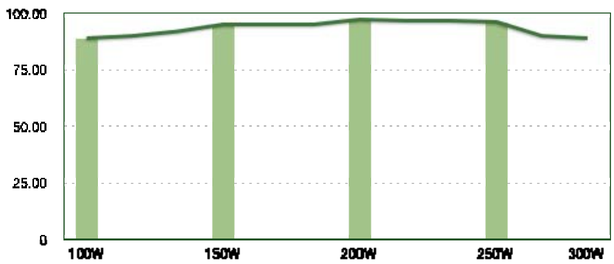

Fig. 13. Efficiency of a Multi-cell Experimental MICroinverter

V. CONCLUSION

Microgrids exploiting small PV generation plants are an increasing popular solution for establishing large scale distributed energy systems. In such systems the electronic converters play a crucial role as they allow optimizing the power flow either from the PV panels either towards the grid. With the aim of showing how important can be the contribution of power electronics in this area, this paper has presented standard and advanced converter topologies that have been compared according to such performance parameters as efficiency, cost, and reliability. Advantages, limitations, and possible applications of the presented configurations have been indicated within the two classes of identified power converters, respectively below few kW and higher than 3-5 kW.

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BIOGRAPHIES

Alfio Consoli, after a period at Fiat in Torino, Italy, working at the R&D unit, has been a professor of Electrical Machines with the University of Catania since 1975, teaching in the areas of electrical machines, electrical drives and power electronics. Since 1980 he has been visiting the USA for research and teaching assignments. His research activities include energy conversion systems, electrical drives, robotics, and power electronics, having been performed in the frame of industry cooperation, national, and international research programs.

He has authored or co-authored over 300 technical papers and holds four international patents. He is co-author and co-editor of the book "Modern Electric Drives" published by Kluwer in 2000. He is also the author of 'Electrical Motors' within the Italian National Encyclopedia 'Treccani'. Among his international achievements, are two IEEE awards respectively for the best paper published in the IEEE Transactions on Power Electronics, and for paper presented at the IEEE-IAS Annual Meeting.

Prof. Consoli is the Past President of CMAE (Converters, Machines, and Electrical Drives) the Association of Italian Professors on Power Electronics. Since 1987 he has been responsible of the Ph.D. program in Electrical Engineering and now is the Coordinator of the Ph.D. program in Energy at the Scuola Superiore of Catania.

He is the Head of CePTIT, the 'Center for Promotion and Transfer of Innovation Technology' at the University of Catania, that he created in 1999.

Dr. Consoli is a Fellow of the IEEE and a Distinguished Lecturer of the IEEE IAS/PELS Societies. He is an Associate Editor of the IEEE Trans. on Power Electronics and a member of the Advisory Committee of the IEEE Power Electronics Society (PELS) as the Chairman of the Motor Drives Committee. He is also a member of the Italian Electric Association (AEI) and a member of the Executive Committee and the International Steering Committee of the European Power Electronics Association (EPE).

Mario Cacciato received the degree in Electrical Engineering cum laude from the University of Catania, Italy, in 1996. In 2000 he received the PhD in Electronic Engineering from the University of Reggio Calabria, Italy.
In 2000 he was with the Department of Electrical Engineering of the University of Rome ‘La Sapienza’ as an Assistant Professor. From 2004 he is with the Department of Electrical, Electronics and System Engineering of the University of Catania, where he is currently teaching Electrical Drives.

The main scientific interests of Dr. Cacciato include power electronics, control of electric drives, electromagnetic compatibility, renewable energies and hydrogen applications. Dr. Cacciato is the author of more than 60 technical papers, published on journals and proceedings of international conferences. He has also participated to several research projects founded by Italian and foreigner agencies such as MIUR, CNR, ENEA, and the European Community.

Dr. Cacciato is a member of the IEEE and AEIT, the Italian Electric Association. Within AEIT, he is presently a member of the scientific board of the Automation Group.

Vittorio Claudio Crisafulli received the MSc degree in Electronic Engineering from the University of Catania in January 2007. Since June 2006 he has collaborating with STMicroelctronics, Catania site, and Dept. of Electrical, Electronics and Systems Engineering of the University of Catania. In January 2008 he was admitted to the International PhD on Energy of the Scuola Superiore - University of Catania. His main interests are in the following fields: industrial switch mode power supply, inverters for UPS, converter and control techniques for Photovoltaic Applications. He has co-authored of some National and International Paper in Power Electronics.