Review on Single-phase PV Inverters for Grid-connected Applications

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Abstract: - In this paper, a review of PV inverters is reported based on converter characteristics as the number of energy processing stages, the presence of a transformer (high-frequency or 50Hz transformer), and the adopted configuration of the PV field. In particular, the considered solutions have been evaluated depending on efficiency, input current ripple and life-time of the capacitors coupling with the solar panels.

Key-Words: - Inverter, current ripple, power quality, life-time, efficiency, resonant converter.

1 Introduction

The growing demand for electricity, the commitment by the leading industrialized countries to reduce the pollution into the atmosphere and the political instability in the countries that are the major producers of traditional fossil fuels, has attracted, over the last decade, the attention of the public opinion and scientific worldwide research in the field of renewable energies [1].

The present national and international energy policies should carefully consider any possible and practical use of non-polluting energy sources. The technologies used to produce energy from such sources as wind, solar, geothermal or biomass, are ready for the market use in some cases, as for the wind, and need further improvements in other cases, as for PhotoVoltaic(PV).

Electricity production from small generation systems (1 to 10 kW), based on PV panels, is now more attractive thanks to the presence on the market of plug-and-play conversion systems while economic incentives are provided by several European governments. The diffusion on a large scale of distributed generation systems connected to the grid, involves many advantages both for the distributor (or utility) institution and for end users in terms of optimization, flexibility and stability of the service system.

Distributed generation systems exploiting solar energy are based on the use of advanced power electronics, since the current conversion processes are associated with switching power converters, advanced Pulse Width Modulation techniques (PWM), and control systems based on one or more microcontrollers. Inevitably, the use of power electronics forces to take into account such issues as cost, efficiency of conversion, "Power Quality", and reliability. Although it is hard to completely solve these issues, it is possible to optimize the generation system at the design stage by adopting conversion topologies that can better afford the requirements imposed by the standards including cost containment.

The PV conversion systems currently used do not take into account such issues as:

- current 'ripple' on the coupling capacitor between the PV field and the converter
- partial solar field shade that can reduce the performance
- not perfect matching of the PV modules characteristics when connected in series or parallel.

The most common PV power conversion system adopts a single- or three-phase voltage source inverter, which is current regulated through a proper PWM modulation technique. The inverter is directly connected to the PV field whose output voltage continuously varies between 500 and 700 V, and is interfaced to the network via a 50 Hz insulation transformer. The system is controlled through an appropriate algorithm called Maximum Power Point Tracker (MPPT), able to drive the operating point of the solar field at its maximum power under all conditions of radiation.

In this paper some solutions are presented that use multiple converters in order to operate the MPPT for a string, or even a panel, to increase the efficiency of the system and the life-time of the coupling capacitors with the solar panels.

2. PV Inverter Characteristics

With the aim to compare different solutions, the most important technical characteristics of PV inverters that can be considered are as follow:

2.1 Input/Output Power
According to its specific design, each PV inverter exploits different characteristics in terms of input/output power. Typically the power values are indicated as the rated DC input, max DC input, and max AC output.

2.2 Topologies
In order to avoid circulation of a DC current on the AC side, that causes saturation and overheating of power distribution transformers, the use of an isolating transformer at the output side of the PV converter is the simplest and most adopted solution to avoid any inconvenience. However, the Low Frequency (LF) transformer in conventional PV converter design is responsible for losses of around 2% in peak efficiency and accounts for the largest part of the inverter's weight and volume. Design without LF transformers is cheaper, more efficient, and lighter. On the other hand, Transformer Less (TL) design needs additional electronics and control components to provide protection from DC injection. In particular, a grounding detection circuit is required in the DC side and a circuit for detecting the DC component in addition to the AC current has to be provided. Even though manufacturers claim that TL inverters can be made as safe as LF design, they cannot be installed in such countries as Italy and Spain for power up to 20 kW. Below 20 kW, the use of TL converters is possible by adopting a protection that detects a DC component in the output current. Because high frequency transformers are small, lightweight, and provide electrical isolation, they are a compromise between the conventional LF and TL design.
In many installations, as different strings can operate under different conditions, a separate DC/DC converter for each string would be used to improve the produced energy. Multi-string technology allows multiple (usually two or three) strings to be connected to a single inverter. Such converters feature a separate MPPT for each string, ensuring maximum energy yield, reducing converter costs for PV systems.
Another feature of last generation PV inverter consists in master-slave function. A "master" converter controls the operation of one or two "slave" inverters, such that the slaves are turned off when the power produced by the field can be processed by a single or two inverters. In this way, inverters always operate at an optimized power level to achieve higher system efficiency.

2.3 Components
IGBTs are almost exclusively used as power switching devices at a switching frequency around 16 to 20 kHz.
As size, weight and cost are strictly related with the number of passive components, topologies with less passives are preferred. Moreover, the PV Converter lifetime is mainly limited by the use of electrolytic capacitors.

2.4 Control strategies
PWM switching strategies can be used in voltage or current control scheme depending if the feedback control signal is the output voltage or current. The current control scheme is mainly used, although some inverters employ the voltage control scheme. The current control scheme is extensively employed because a high power factor can be obtained with a simplest control circuit, and transient current suppression is possible when disturbances such as voltage changes occur in the utility power system. Current control scheme hardly allows operation as an isolated power source but there are no problems with grid-connected operation.

3 Configuration of PV Systems
The problems concerning the connection of a distributed generation system with the public grid are many and sometimes of difficult solution. Among them, issues as precise control of sinusoidal current injection into the grid and maximum energy extraction from a PV field are very sensitive. As a matter of fact, it is well known that the characteristics of PV modules are strongly nonlinear depending on the conditions of temperature and radiation, as shown in Fig. 1.
The effect of such non-linearity is shown in the variation of the available level of output power from the generator when a varying load impedance is connected, for certain conditions of temperature and solar radiation. Such an effect may be compensated by using a DC/DC converter that, exploiting a MPPT control algorithm, realizes the impedance adaptation necessary to maximize the energy produced from the PV field [2]. The connection to the distribution grid is subordinate to the observance of all laws and regulations (CEI 11-20, IEC 64-8, CEI EN60947-4-1, CEI EN 50263, EN 61000-3-2, IEEE 1547) which establish the criteria for connection and disconnection (anti-islanding).
Some of the main requirements that have to be considered in case of the connection of a system

with a power peak of 3,7kW, which are indicated in EN 61000, are shown in Table 1.

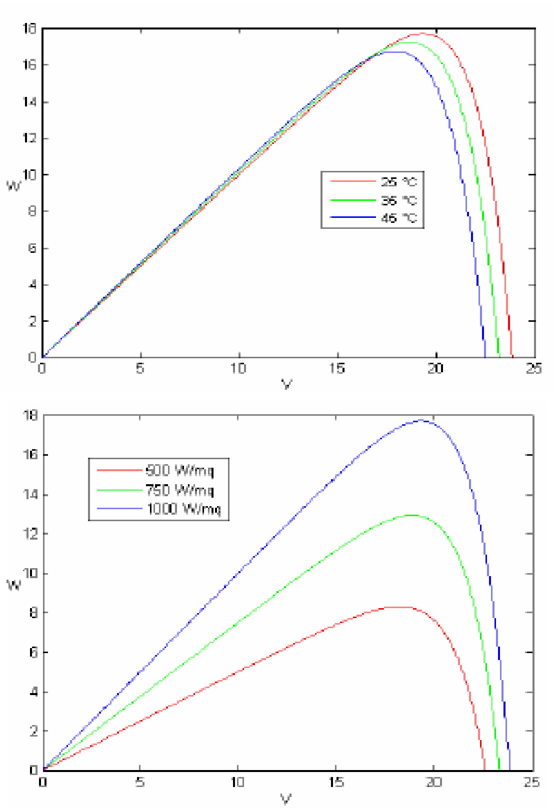

Fig. 1 - Current-Voltage(up) and Power-Voltage(down) characteristics of a PV module.

Table 1: Technical specifications for grid connection.

Specifications	**EN 61000**
Nominal Power [kW]	<=3,7
Amplitude of Current Harmonics [A]	(3) 2,3 (5) 1,14 (7)0.77 (9) 0.4
THD	<=5%
Maximum DC current value [A]	<0.22
Voltage range	0,8 – 1,2 V_n
Frequency range [Hz]	49 – 51

The general block scheme of a PV system includes photovoltaic panels, which convert solar energy directly into electrical form in DC, a storage system, and a DC/AC converter. DC/AC converters used in PV systems, can be firstly classified by considering the number of energy processing stages used. In particular, it is possible to consider single-, dual-, and multi-stage inverters. Other features, that allow a further classification, concern the use of a LF or HF transformer, where the capacitors used to decouple the primary source and inverter are connected and, finally, the type of inverter used: voltage or current source. Moreover, the configuration of photovoltaic field allows a further classification because can consists in one or more strings connected in series and parallel, or in one or more panels connected in strings.

3.1 Single stage or centralized inverters

In the past, the easiest way to interface a large number of PV modules to the network was the use of single of three phase centralized inverter, depending if the power were below or above 6 kW. In this configuration, the modules are connected in series to create strings with output voltage high enough to avoid an additional voltage boost stage. In order to obtain the desired power level, the strings are connected in parallel through interconnection diodes (string diodes), as shown in Fig. 2. Although this configuration is widely used, especially for high power values of PV fields, it shows many drawbacks. First of all, the global efficiency of the generation system is effectively reduced [3]. The main reason of reduced performance is due to the centralized MPPT control that fixes a common operating point for all PV modules. Because of modules Maximum Power Point (MPP) variation with temperature, manufacturing imperfections, age, and partial shade, a different operating point should be adopted for each module in order to extract the maximum power from the source. Moreover, some drawbacks are the presence of string diodes, which introduce additional losses, and the use of a LF transformer determining an increase of cost and weight of the converter.

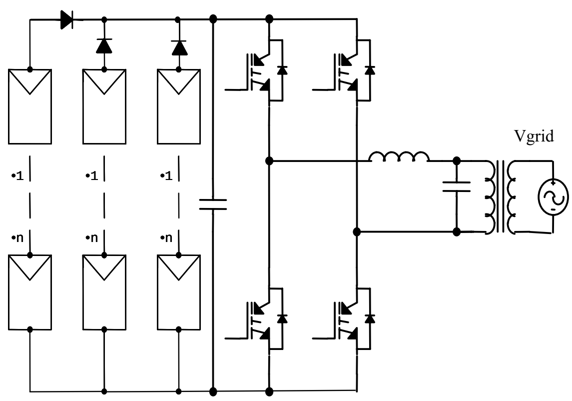

Fig. 2 -Configuration phase inverter single stage.

3.2 Double and multi stages inverters

A more advanced technology is based on the use of photovoltaic fields arranged in strings rather than arrays. Each string is then connected to a double- or a single-stage inverter. According to the number of series connected PV modules per string, and only if

the resulting voltage is sufficiently high (at least 360V), the DC/DC converter can be omitted. In this last case, a large number of modules connected in series are required in order to obtain values of open circuit voltage higher than 360V. On the other hand, with a DC/DC boost converter, the energy conversion can also be performed on strings characterized by low output voltage, resulting from the connection of a few number of PV modules. In any case, multi-string inverters, featuring either a double or single conversion stage, allow increasing the efficiency of the generation system. This is mainly due to the absence of string diode losses and to a more efficient MPPT performed on each string.
Another topology adopted by some manufacturers and still applied to the multi-string/multi-stage concept, consists in the use of a high voltage DC bus where two or more DC/DC outputs are connected according to the number of strings linked at the input terminals to obtain the desired output power level. The DC bus voltage is then used to feed a single- or three-phase inverter. Actually, this configuration is more complex than the previous ones but, nevertheless, adopted by different companies producing photovoltaic inverters. Indeed, the added complexity is compensated by greater flexibility and better overall performances. Consequently, system efficiency is higher due to the application of MPPT control on each string and higher flexibility comes from the ease of extensions for the photovoltaic field. Even the so-called "AC modules", obtained by the combination of a photovoltaic module and a multi-stage inverter for grid connection are based on the same design criteria, as shown in Fig. 3.

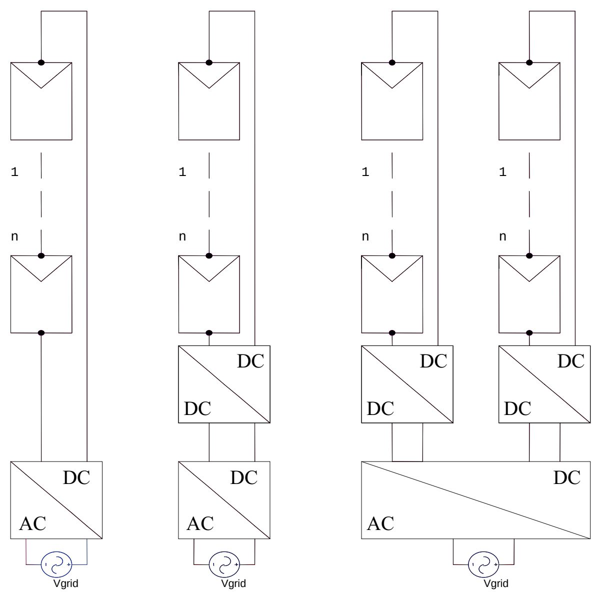

Fig. 3 – Single converter (MPPT) for each string.

In this case, it is always necessary to increase the output voltage of the PV module with a DC/DC boost converter characterized by high voltage conversion ratio.
Such a feature can be obtained using a HF transformer or by the cascade connection of two or more amplification stages if galvanic isolation between the primary source and the utility is not required.

4 Main Inverter Topologies

The choice of conversion topology is, as mentioned above, strongly dependent on the PV field configuration and its power peak. Generally, for powers greater than a few tens of kilowatts, single-stage configuration, as that shown in Fig. 2, are preferred. However, most innovative diagrams conversion schemes, as shown in Fig. 4, can also be adopted.
The first one is a multi-phase inverter showing a better efficiency than classical half- or full-bridge configuration. The corrected operations are only guaranteed for a bus voltage value higher than about 360V. The main drawback is constituted by the poor management of the energy that is potentially available from the PV field. Such a problem is partially solved in the second configuration of Fig. 4, where the balancing voltage circuit of capacitors C_1 and C_2, and the half-bridge configuration, allows a better use of the available energy. The MPPT control can also be applied independently on each string. Topologies using a multi-string configuration for the PV field and a multi-stage for the converter are more convenient for power levels below 10 kW.

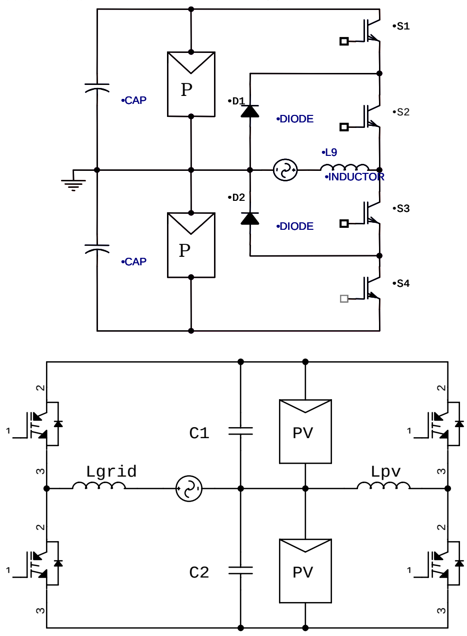

Fig. 4 - Non-standard configurations of single stage inverters.

Two of the most interesting solutions, already on the market, are shown in Fig. 5. Both solutions have three DC/DC boost converters, without isolation in the first case, and isolated through a HF transformer in the second, while the DC/AC converter can be half- or full-bridge type. The decoupling capacitors, which are the weak components of the system, are in both cases, connected on low voltage side in parallel with the strings. A topology that allows to reduce the size of decoupling capacitors, through a reduction of the current ripple, is shown in Fig. 6. The reduced current ripple is achieved thanks to the interleaved

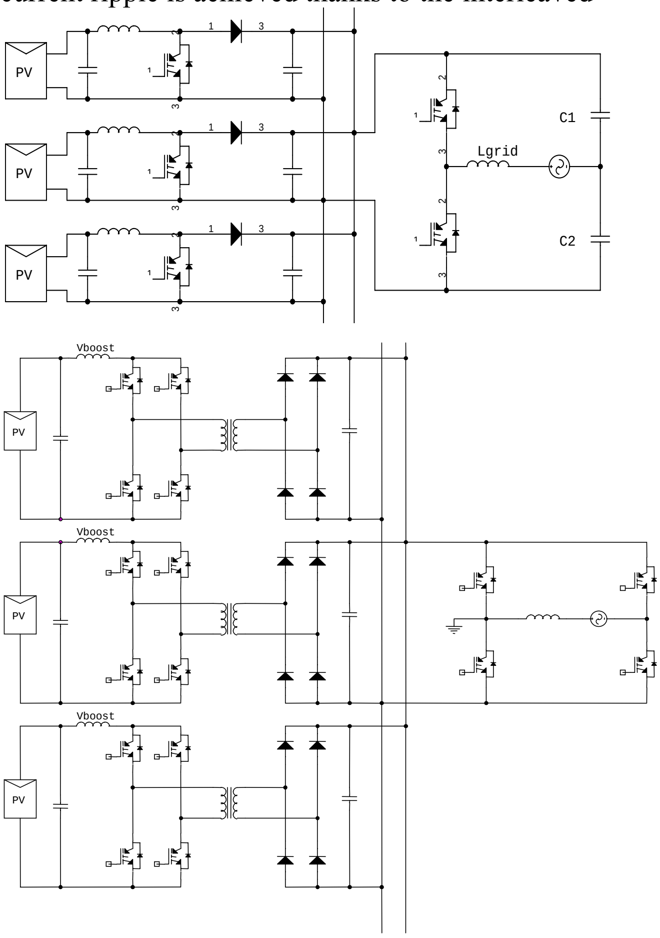

Fig. 5 – Multi-string/multi-stage configurations.

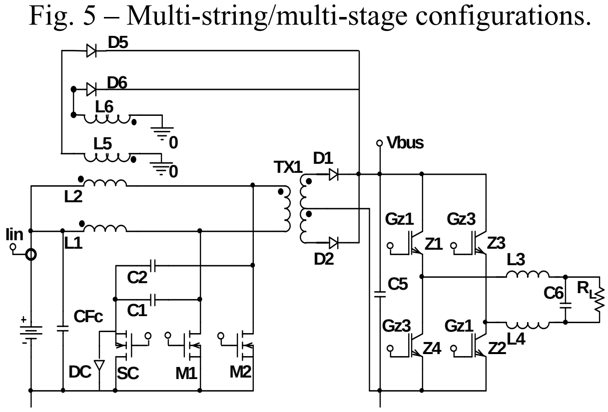

Fig. 6 –Converter for ripple reducing of the input current.

modulation of the power devices in the DC/DC stage [4][5].

A particular class of PV inverters is that featuring HF-link [6]. In this case, the DC/DC converter is suitably controlled in order to properly shape the current according to a sinusoidal envelope. Such a current waveform, adequately filtered, is injected into the grid through an inverter switching at 50Hz, i.e. at low frequencies, greatly reducing the commutation losses of the power devices.

Another class of converters, whose performance evaluation has been recently started by manufactures, is represented by Zero Voltage Transition (ZVT) phase shift converters. Among those, the FB phase-shift converter is already used in telecom and server applications where high power density and high efficiency are mandatory. Active bridges, firstly introduced in [7] also exploit the phase shift concept in order to achieve Zero Voltage Switching (ZVS) for the power devices. An innovative converter has been proposed in [8], achieving significant reduction of production costs and high efficiency. The converter scheme is shown in Fig. 8 and is composed of an input bridge connected to a controlled voltage doubler (M5, M6) through an HF transformer, and an FB inverter used to generate a controlled 230Vrms, 50Hz sinusoidal voltage.

The voltage doubler, connected to the secondary side of the transformer, is adopted to decrease the transformer turns ratio, simplifying the winding structure and minimizing the required window area.

5 Conclusion

In the paper, some of the most interesting and relevant converters for PV applications are considered and classified. Some issues, like costs reduction and efficiency maximization, has been addressed and many solutions have been proposed. Other problems, like the converter life-time especially for some critical components as electrolytic capacitors, are still being studied and not completely solved.

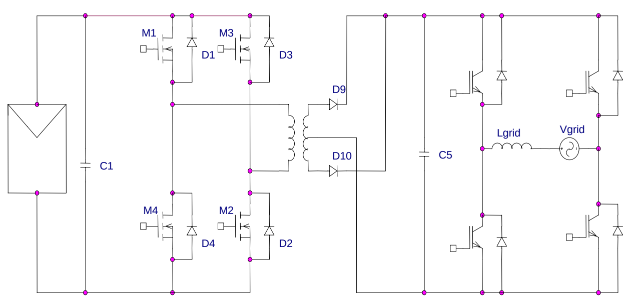

Fig. 7 – HF-link topology.

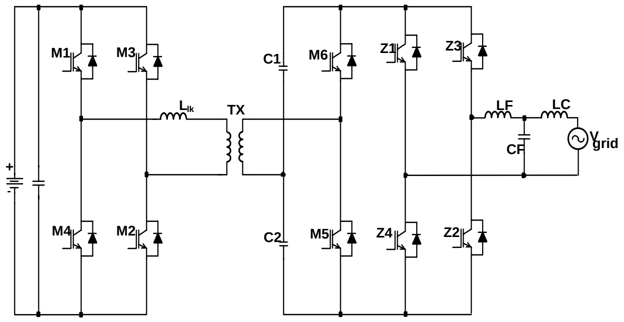

Fig. 8 - Zero voltage switching phase-shift converter.

Today, topologies with classic single-stage inverter appear replaced by multi-string configurations with dual-stage inverter.

It is foreseeable that future technological developments will enable the integration of the conversion system within the photovoltaic module. In such a way, for small power PV field, the converter will not exists anymore as a separate component.

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