International Journal of Research (IJR) Vol-1, Issue-9, October 2014 **ISSN 2348-6848**

A Review of Single-Phase Grid-Connected Inverters for Photovoltaic generation system

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ABSTRACT

This review focuses on inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid. Various inverter topologies are presented, compared, and evaluated against demands, lifetime, component ratings, and cost. Finally, some of the topologies are pointed out as the best candidates for either single PV module or multiple PV module applications. The inverters are categorized into different classifications such as the number of power processing stages in cascade, the type of power de-coupling between the PV module(s) and the single-phase grid, whether they utilizes a transformer (either line or high frequency) or not, and the type of grid-connected power stage.

Key words- *AC module; photovoltaic (PV) power systems; single-phase grid-connected inverters*

1. GRID-CONNECTED ELECTRONICS

Multiple solar cells connected to form a PV module. The simplest PV system consists of 300 watts. One or more of these modules are connected to an inverter which convert direct-current (DC) output of other modules into alternating current (AC). Optionally, batteries may provide energy storage or backup power in case of a power interrupting or outage on the grid. Grid-Tie Inverters Most residential households will use a grid-connected PV system. In this scenario, in a grid-tie inverter (GTI) is used to complement the generated solar power with grid power. In addition to regulating the Voltage and current received from the solar panel, a GTI ensures that the power supplied to the distribution panel of the house will be in phase with the grid power. On the DC side, maximum power point tracking (MPPT) optimizes the power output by varying the closed loop system voltage. On the AC side, these inverters ensure that the sinusoidal output is synchronized to the grid frequency (nominally 60Hz

2-EVOLUTION OF PV INVERTERS

As shown on Fig 1. Inverters are connected in into series, called strings, generating a sufficient high voltage to avoid amplification. All strings are then connected in parallel to support high power to output. Only one inverter is utilized to interface the grid. This technology suffers from disadvantageous issues, including high voltage DC cable from a big number of strings to the inverter and losses in string diodes. This structure is also limited from Maximum Power Point (MPP) Tracking and controlling mismatch between strings so individual PVs, resulting in low efficiency and reliability. The nonflexible design makes it less appealing in mass production.

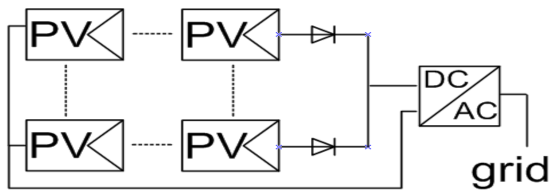

Figure 1 Fig 1. Inverters are connected in into series, called strings

2.1 STRING INVERTER

This technology, shown in Figure 2, illustrates effort to solve problems of the previous design. It has a string of inverters connected in series with an AC module. While still avoiding high voltage amplification, this structure has improved performance with no diode loss in series, separate MPP tracking for each string and lower cost with mass productions. The inverter can be implemented with high voltage MOSFET/IGBT. It is possible to have less PV in string with voltage amplification by DC-DC converter or a line frequency transformer, which increases total area. Although having been introduced to the market for about 10 years, this structure remains a favorite structure in new installation. However, in a common scenario of partial shading, MPP tracking may still not be sufficient to achieve a certain efficiency requirement.

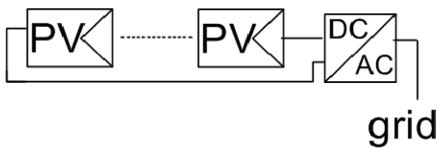

Fig 2. String of inverters connected in series with an AC module

2.2 MICRO-INVERTERS

The micro-inverter solution, also called AC module, shown in Figure 3, is the integration of PV and inverter into one electrical device. With only one PV to control, there is no PV mismatch. MPP tracking can be done at individual PV level, maximizing possible efficiency. As it is modularized, the micro-inverter is good for mass production, which potentially leads to low manufacturing cost and low retail prices. This technology is also very appropriate for residential applications with low power requirements and where partial shading is a critical issue. This type of inverter is also designed with a "plug and play" feature so that it can be installed without a deep electrical knowledge. However, if implemented by a big number for industrial applications, due to the distributed installation, the maintenance requirements can increase the cost and discourage wide usage. To keep inverter boxes watertight and use components that have large temperature ambient is major concerns. It will be necessary to develop a system that can detect failure of any micro-inverter and isolate it immediately. This type of inverter has recently become emerging product and promised a remarkable market share in future.

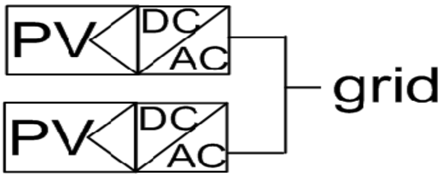

Fig 3. Integration of PV and inverter into one electrical device

2.3 MULTI-**STRING INVERTERS**

Multi-string inverter, shown in Figure 4, features the optimal MPP tracking for a single string of PVs. In this structure, DC-DC converter is implemented for each string for MPP tracking and power combination of different string to a DC bus. A big power stage works as a grid connected half bridge inverter without transformer. The multi-string inverter is useful when PV strings of different rated power, different orientation are combined. The DC-DC part can be implemented with high-frequency pulse width.

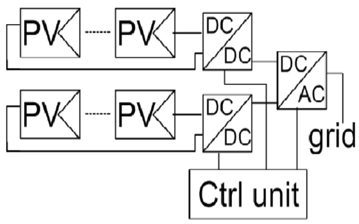

Fig 4. Features the optimal MPP tracking for a single string of PVs

PV-modules are connected in combinations of series and parallel configurations to get a higher power level for the PV-system. Very common is a series connection of modules (the cells inside the modules are connected in series, too). The series connection of modules is called a string. The voltage of such a PV-string can be between 150 V and 1000 V for today's grid connected

PV-systems. DC-voltages which are higher than the peak voltage of the grid (325 V DC for 230V-AC-grids) have the advantage that the inverter does not need to step-up the voltage by a DC/DC-stage or a transformer

Fig 5. A single power processing stage that handles the MPPT, voltage amplification, and grid current control

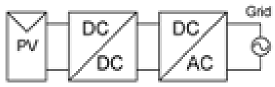

Fig 6. Dual power processing inverter where the dc–dc converter is responsible for the MPPT and the dc–ac inverter control the grid current. Voltage amplification can be included in both stages.

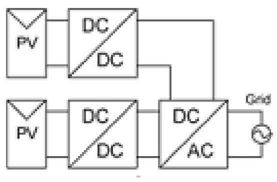

Fig 7. Dual-stage inverter, where each PV module or string is connected to a dedicated dc–dc converter that is connected to a common dc–ac inverter

3 FUNCTIONAL BLOCKS AND TOPOLOGIES OF PV-INVERTERS

Five basic functions can be identified for all PV-inverters:

1. MPPT FOR THE DC-INPUT The inverter controls the DC-voltage in order to operate the PV-modules at their maximum power point. The MPP varies with the insulations, the module temperature and the shading conditions. Therefore sophisticated tracking algorithms are used. For good efficiency of the MPPT it is important that not only the mean values of voltage and current of the module are tracked to the MPP, but also the behavior at higher frequencies has to be considered. If the power electronic topology of the inverter introduces a voltage ripple at the PV-terminals, that ripple has to be kept small. Otherwise the operating point of the PV-generator would not stay stable in the MPP at all times. Most state of the art string-inverters use a one-stage topology (for example a full-bridge), in which the DC-link is directly connected to the PV-input. By controlling the grid current (and thus the power delivered to the grid) the DC-link voltage can be influenced. But also topologies with a separate DC/DC-stage for MPPT can be found.

2. CHANGE OF THE VOLTAGE AMPLITUDE If the PV-inverter uses a voltage sourced inverter (VSI) as a grid interface, this inverter has a buck-characteristic. This means that its output voltage is always smaller than the input voltage. If the PV-system delivers a voltage that is smaller than the peak value of the grid voltage, a voltage boost is needed. This can be done with use of a transformer or by a DC/DC-stage (e.g. boost converter).

3. **GRID INTERFACE** This is the main function block of the inverter. Most common is the use of a VSI. It can be build as a standard full-bridge for inverters with a transformer at the AC-side.

4. **POWER DECOUPLING BETWEEN DC- AND AC-SIDE** the power fluctuations between DC- and AC the grid frequency for single-phase inverters has to be decoupled by energy storage. Most common are electrolytic capacitors forming a DC-link. Because the minimization of the AC-side of the inverter switching frequency DC-link-capacity seems to be essential to achieve higher inverter lifetimes (film-capacitors could be used) a trend to 3-phase-inverters can be expected even for smaller power levels within the 1.5 kW range .

5. **GALVANIC ISOLATION BETWEEN INPUT AND OUTPUT** Can be achieved by the use of transformers. Classically transformers operated at grid-frequency are used, which have severe drawbacks like high weight, high cost, additional losses and a non-unity power factor,

especially under low load conditions. New developments use high-frequency transformers. A third solution is to leave out the transformer and the isolation between input and output of the inverters. The resulting transformer less inverter has very high efficiencies, a low weight and has lower costs. The commercial inverter SMC8000TL from SMA reaches a peak efficiency of 98%.

4. INVERTER TOPOLOGY Inverters can be classified by their output waveform in four categories: square wave, modified square wave, also called quasi- square wave, multilevel and sine wave (synthesized from a high frequency PWM), Although the square and quasi-square wave inverters can be accepted in some applications, and are available in the market, they are not recommended due to their poor quality waveform. Multilevel and sine wave inverters are considered the state of the art technology. The main difference between the two topologies is the switching frequency, the former based on low frequency while the later based on high switching frequency multilevel inverters are the best available solution for high power applications. However, for medium and low power applications, there is not a clear tradeoff to make it more appealing than sine wave inverters, or vice versa. High frequency inverters favor compactness and reduced cost, while low frequency ones are claimed to have the best efficiency and robustness. The final choice of one inverter instead of the other better depends on the application. In our application stand-alone renewable energy systems (SARES), multilevel inverters have great potential with its reliability, surge power capacity and efficiency.

5. MULTILEVEL INVERTERS Fig. 8 shows one multilevel inverter topology example, implemented by cascade H-bridge. The timing diagram depicts how it works. The operation of a multilevel inverter can be described as an optional stacking of a number of DC voltage source stages. Dependent on a certain time of operation that one stage is stacked (forward or reverse) or bypassed. Output distortion and EMI. Voltage stress on devices of each With multi-steps, multilevel inverters have low stage is a fraction of overall voltage rating, allowing high performance devices with low voltage rating, improving efficiency. Voltage and current harmonics are also significantly reduced. Multilevel PWM and step modulation can be

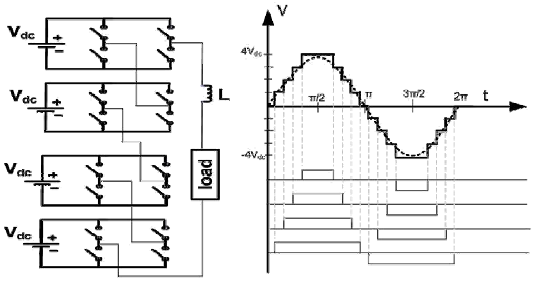

Fig 8. Cascade H-bridge multilevel inverter and operation.

used to synthesize voltages with high spectral quality even at low switching frequency. Small-step feature means low dv/dt stress, thus, relaxing electro-magnetic compatibility (EMC) requirements. Beside the advantages, multilevel inverters also have some issues, such as requiring a big number of semiconductor switches, which increased as the number of steps/levels increases, and complex design for synchronous gate drivers for different levels.

6. MULTILEVEL INVERTER TOPOLOGY

There are many types of multilevel inverter topologies in its history, starting from the series H-bridge design, followed by the diode-clamped, which utilizes a bank of capacitors to split the DC bus voltage, and then the switched flying capacitor (or capacitor-clamped) topology. An inverter design can also cascade these fundamental topologies to make hybrid topologies to improve power quality. The main multilevel inverter topologies are Diode clamed, switched capacitor, cascade H bridge-Transformer less Bi direct DC-DC, Multiple transformers.

7. POWER DECOUPLING

Power decoupling is normally achieved by means of an electrolytic capacitor. As stated earlier, this component is the main limiting factor of the lifetime. Thus, it should be kept as small as possible and preferably substituted with film capacitors

7.1 DIFFERENT LOCATIONS FOR THE POWER DECOUPLING CAPACITOR.

7.1.1 Capacitor is placed in parallel with the PV modules, in the case of a single-stage inverter.
7.1.2 Capacitor is either placed in parallel with the PV modules or in the dc link, in the case of a multi-stage inverter.

7.2 EXAMPLES OF TRANSFORMER-INCLUDED INVERTER SOLUTIONS.

7.2.1 Line-frequency transformer (LFT) is placed between the grid and the inverter (solves problems with injection of dc currents into the grid.

7.2.2 High-frequency transformer (HFT) is embedded in an HF-link grid-connected ac/ac inverter.

7.2.3 Transformer less high-input-voltage PV inverter with single-phase common-mode (CM) and differential mode (DM) EMI filters.

8. CONCLUSION

This review has covered some of the standards that inverters for PV and grid applications must full fill, which focus on power quality injection of dc current to the grid, detection of islanding operation, and system grounding. The demands stated by the PV modules have also been reviewed. The role of power decoupling between the modules and the grid has been investigated. An important result is that the amplitude of the ripple across a PV module should not exceed 3V in order to have a utilization efficiency of 98% at full generation Finally the basic demands defined by the operator have also been addressed, such as low cost, high efficiency, and long life time .t he next part of the review was a historical summary of the solutions used in the past, where large areas of PV modules were connected to the grid by means of centralized inverters. This included many short comings for which reason the string inverters emerged. A natural development was to add more strings, each with an individual dc–dc converter and MPPT, to the common dc–ac inverter, thus, the multi-string inverters were brought to light. This is believed to be one of the solutions for the future. Another trend seen in this field is the development of the ac module, where each PV module is interfaced to the grid with its own dc–ac inverter.

9. ACKNOWLEDGEMENT

This paper is supported completely by RTM University Nagpur (maharastra) india .The author would like to thank prof. U .T. Nagdeve their help given during preparation of this paper.

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