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Evolution of Single Phase Photovoltaic Inverters

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Abstract - This brief review focuses on inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid. The inverters are categorized into four classifications: 1) the number of power processing stages in cascade; 2) the type of power decoupling between the PV module(s) and the single-phase grid; 3) whether they utilizes a transformer (either line or high frequency) or not; and 4) the type of grid-connected power stage. Various inverter topologies are presented, with issues related to grid connected & standalone applications.

Index Terms—AC module, photovoltaic (PV) power systems, single-phase grid-connected inverters

I. INTRODUCTION

According to the U.S.A. Energy Information administration [1], world energy consumption is likely to increases by 53 percent, from 505 quadrillion Btu in 2008 to 770 quadrillion Btu in 2035. The effect of global warming and abnormal climatic changes needs a large reduction in greenhouse gas (GHG) emissions. This prevents adding of new power plants, which use conventional energy sources namely burning of primary fossil fuel such as coal, oil, natural gas, etc. [2].This presents significant opportunities for distributed power generation (DG) [3] system using renewable energy resources such as solar, wind and fuel cells. Both consumers and power utilities can benefit from the widespread deployment of DG systems which offer secure and diversified energy options, increase generation and transmission efficiency, reduce greenhouse gas emissions, improve power quality and system stability, cut energy costs and capital expenditures, and alleviate the bottleneck caused by distribution lines.

II. DISTRIBUTED POWER GENERATION (DG)

DG systems are usually small modular devices close to electricity consumers. These include wind turbines, solar energy systems, fuel cells, micro gas turbines, and small hydro systems, as well as the relevant controlling/managing and energy storage systems. Such systems commonly need dc–ac converters or inverters as interfaces between their single-phase loads and sources as shown in Fig. 1(a) & 1(b), which depicts a typical renewable DG system using photovoltaic (PV) as energy source. DG inverters often experience a wide range of input voltage variations due to the fluctuations of energy sources, which impose stringent requirements for inverter topologies and controls.

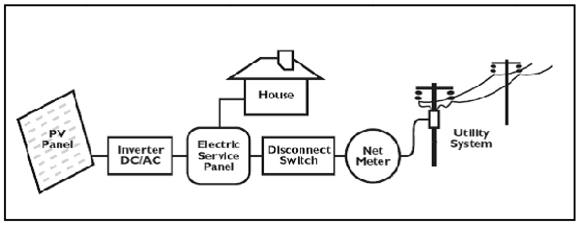
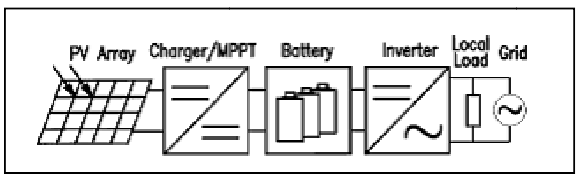


Figure 1: (a) lay out of a renewable DG system using photovoltaic (PV) as energy source



1(b) Block diagram of a photovoltaic system.

This paper starts with a historical overview. In the past, a large no of PV-modules were interfaced to a centralized inverter. Where as in the present time, decentralized inverters are interfacing a single or few modules of PV cells. The future technology will be where inverter only interfaces a single PV-cell to the grid. In the next section an overview of existing power converter topologies for the AC-Module is given. The approaches are further discussed in order to compare the topologies for future applications.

III. TECHNOLOGICAL TRENDS

Technologically the inverters are developed based on two areas such as

1. Power handling devices which decide the rating
2. Signal processing which decides power conditioning

In earlier days power transistors were used to the maximum extent. The development of high power rated MOSFET and IGBT'S have replaced transistors in the power handling section. Signal processing has advanced rapidly with the development of cheaper and feature rich microcontrollers and digital signal processors. Another required trend is the smaller size with larger power handling capacity. All these can be achieved by adopting high frequency PWM technique.

Very little R&D has been done for inverter in India. All that has been done is actually the change in design and development of new topologies.

(a) ***A. The Past: Centralized Inverters:*** The past technology was based on centralized inverters, which was interfaced to a number of modules. The modules were normally connected in both series and parallel in order to reach a high voltage and power level. This results in some limitation such as the necessity of high voltage DC cables between the modules and the inverter, power losses due to a centralized MPP Tracking (MPPT) [4].

If one of the modules in a string becomes shadowed, then as a consequence it will operate as a load with lower power generation. On the other hand, if the modules are connected in parallel, the shadowed module is still generating power, but the input voltage to the inverter is inevitably low due to the parallel connection. A third scheme is given in [5], where each module is interfaced by a Generation Control Circuit (GCC). Hence, an individual MPPT is assured for every single module, which also lowers the possibilities of hot spots in PV modules.

Full shadowing of one PV-cell (in a string of 160 cells) causes a temperature rise, inside the cell, of more than 70 ºC above the ambient temperature, whereas the non-shadowed cells only reach 22 ºC above the ambient temperature (for an ambient temperature equal to 12 ºC). This is of great importance because an overheated cell rapidly decreases the module's lifetime.

(b) ***The Present: String Inverters and AC-Modules:*** The present technology, which is a hot research topic, is the 'string-inverter'. String-inverters use a single string of modules to obtain a high input voltage to the inverter. However, the high DC voltage requires a skilled electrician to perform the interconnections between the modules and the inverter. On the other hand, there are no losses 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.

The AC-Module, where the inverter is an integrated part of the PV-module, is also an interesting solution [6], [7]. It removes the losses due to mismatch between modules and the inverter, as well as supports optimal adjustment between the module and the inverter. Moreover, the hot-spot risk is removed. Due to this a better efficiency may be achieved. It also includes the possibility of an easy enlarging of the system due to the modular structure. The opportunity to become a 'plug and play' device, which can be used by persons without any education in electrical installations, is also an inherent feature.

C) The Future: AC-Modules and AC-Cells: The future technology could be the AC-Cell, which is the integration of one great PV-cell and the inverter [8]. 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 low voltage up to an appropriate level for the grid-connected inverter and at the same time to reach a high efficiency. For the same reason, entirely new converter technologies are required.

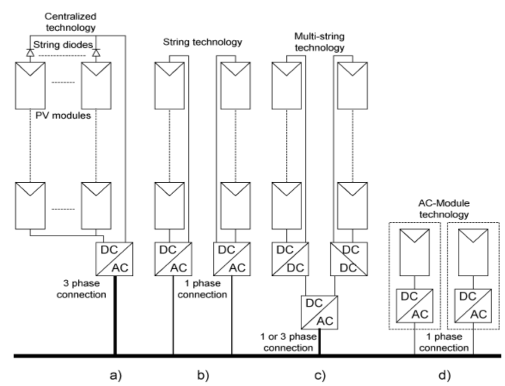


Figure 2: Historical overview of PV inverters (a) Past centralized technology (b) Present string technology. (c) Present and future multi-string technology. (d) Present and future ac-module and ac cell technologies.

IV. INVERTER TOPOLOGIES

Based on the electrical isolation between the input and output, inverters can be classified as isolated inverters or non-isolated inverters. While electrical isolation is normally achieved using transformers, a choice can be made between using line-frequency transformers or high-frequency transformers. The dc-link voltage of inverters for DG systems may vary over a wide range. Depending on the input dc voltage range in comparison to the output ac voltage, inverters can be buck inverters, boost inverters, or buck-boost inverters. It should be noted that although a full bridge inverters are buck inverters by themselves, the whole topologies eventually represent boost or buck-boost inverters due to

PWM operations and voltage step-up in either low frequency or high frequency.

Traditional full-bridge buck inverters are used in many existing high power applications with bulky and heavy line-frequency transformers. However, modern power electronic converters tend to use “more silicon and less iron.” This leads to the pursuance of compact designs with wide input voltage ranges and improved overall efficiency. Broadly PV inverters are classified as

(i) single-stage and

(ii) multiple-stage power circuit topologies

(a) Single-Stage Inverters: The inverter in Fig. 3 has a simple circuit topology and low component counts, leading to low cost and high efficiency. Such a system also demonstrates robust performance and high reliability. This represents a preferred choice of topology as in [9] if performance requirements can be met. However, line-frequency transformers demand a premium in volume and weight, and thus are increasingly replaced by high-frequency transformers or transformer less designs**.**

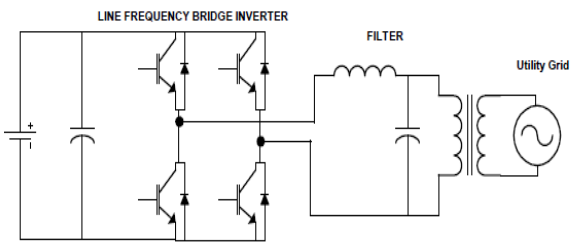


Figure 3: Single stages Inverter with line frequency transformer

Intended to both minimize the power components and step up voltage, single-stage boost or buck-boost inverters were proposed in [10]–[14]and [15] which accomplishes boosting and inverting functions in a single power stage. These converters work on boost or buck-boost principles and use dc inductors for energy storage or fly back transformers for both energy storage and electrical isolation as required for safety reasons.

Single stage inverters may further be classified as 1) four-switch topologies; 2) six-switch topologies.

Four-switch topologies: A non-isolated boost inverter by Cáceres and Barbi [10] is shown in Fig.4, where the dc inputs of two identical boost dc–dc converters are connected in parallel with a dc source and the load is across the two outputs. Each converter is modulated to produce a unipolar dc-biased sinusoidal output, 180 degree out of phase with the other. Thus the output across the load shows a pure sinusoidal waveform.

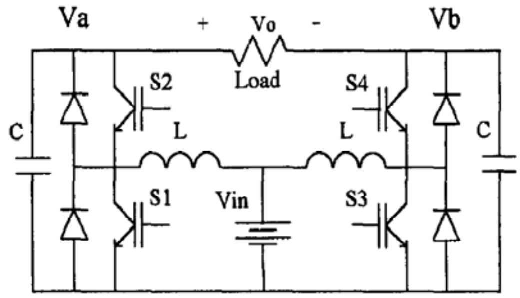


Figure 4: Four-switch boost inverter by Cáceres and Barbi

Six-Switch Topologies: An isolated flyback buck-boost inverter by Nagao and Harada [13] in Fig.5 combines two buck-boost choppers in a four-switch bridge with two additional switches used for synchronous commutation in each half cycle of ac output. Advantages of this inverter include a desired output power regardless of the dc voltage and the electrical isolation between the PV and the utility. Additional switches compared to four-switch topologies facilitate the grounding of both the grid and PV modules.

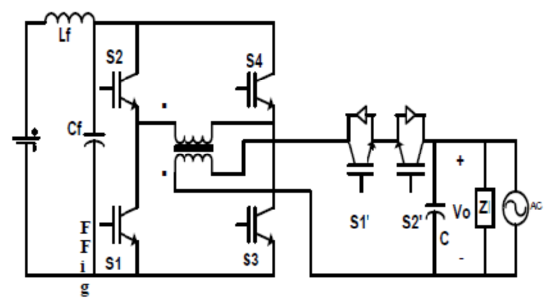


Figure 5: Six-switch isolated buck-boost inverter (isolated)

A distinctive feature of single-stage buck-boost inverters is the elimination of low frequency transformers. Therefore they present a compact design with a good performance-cost ratio compared to conventional buck inverters with line-frequency transformers. Although single-stage inverters are generally high-efficient and low-cost, they usually suffer from

(i) limited power capacity,

(ii) compromised output quality,

(iii) Limited operation range imposed to dc sources.

It is observed, that in such an inverter, the currents through main switches are usually discontinuous triangular pulses, and the output current cannot be controlled directly by the current through power switches even in the continuous conduction mode (CCM) operation. Increasing the power capacity will impose excessive peak current stresses on the power switches. Thus the power capacity of this type of inverters is limited due to cost and size considerations. Therefore, in certain applications where high power, high performance and wide input voltage range are required, multiple-stage inverters are often used.

(b) Multiple-Stage Inverters: In a multiple-stage power inverter, e.g., a two-stage inverter, boost and isolation (if necessary) are carried out in the first stage while the inversion is conducted in the second stage. Each stage can be controlled individually or synchronously. Various multiple- stage topologies are adopted to implement the buck-boost function of an inverter. For the buck or boost operation, either a dc–dc converter or dc–ac–dc converter can be used in the first stage. For the choice of dc-link, the system can be configured with a dc-link followed by a PWM inverter, or a pseudo-dc-link followed by a line-frequency operated inverter.

DC-DC-AC Topologies: By adding a boost dc-dc converter in front of a buck inverter, a two-stage boost inverter is formed as depicted in Fig. 6 which is commonly used in small wind systems [9]. In this structure, an elevated dc voltage with tolerable ripple is obtained in the first stage; afterwards in the second stage, a high frequency PWM buck inverter is used to generate required ac waveforms. There is no need to synchronize between two stages and the output power is usually controlled in the second stage.

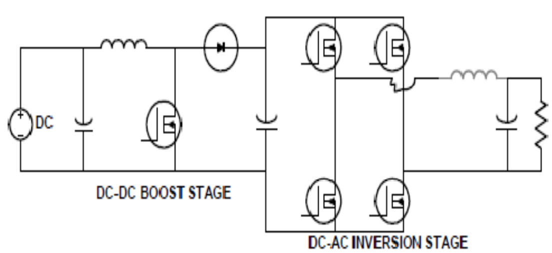


Figure 6: Two-stage boost inverter [9].

DC–AC–DC–AC Topologies: Multiple stage inverters with a high voltage boosting ratio normally consist of a high frequency DC-AC-DC converter to realize a controlled boosted DC voltage from a variable low DC voltage. The boosted DC voltage acts as input for the inversion stage. Fig 7 shows a multi stage DC-AC-DC-AC topology.

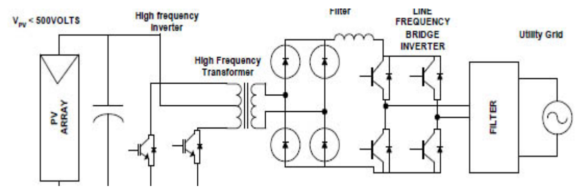


Figure 7: PV inverter with several conversion stages and high frequency transformer

DC–AC–AC Topologies: In DC-AC-AC topology the second stage is a bidirectional ac-ac converter, without an intermediate dc-link, in order to eliminate the bulky intermediate dc-link filter components as seen in most multiple-stage boost inverters. The topology also includes a high-frequency transformer for voltage level change and electrical isolation. Such a topology is proposed by Beristáin *et al.* [16] as shown in Fig. 8. Review of multiple-stage topologies for DG systems shows that it is desirable to use a high frequency transformer in front stages to increase the boosting ratio and provide necessary electrical isolation, and to use a line-frequency inverter in the last stage to reduce total switching losses.

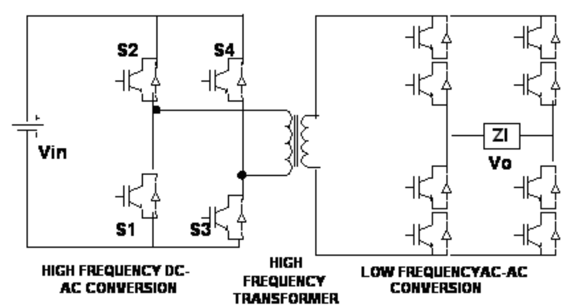


Figure 8: DC-AC-AC topology

However, as mentioned before, a multiple-stage inverter has two or more stages of power conversion to achieve a wide input voltage range and a large power capacity as compared to a single-stage inverter at the cost of additional power components and losses.

IV. GRID CONNECTION ISSUES

Different DG resources have different requirements to their inverter systems. For photovoltaic applications, direct connection to PV array imposes stricter power decoupling requirements to single-phase inverters than the connection after an independent MPPT controller, which is usually implemented by an additional dc–dc converter. The common challenge for DG inverters can be summarized as to extract the most of energy from the sources under the various DG resources conditions.

A. Power Decoupling: Power decoupling between the DG resource and grid is essential, especially for a directly PV-fed single-phase inverter system, since the power generated by PV modules is constant at the maximum power point whereas an ideal single-phase ac load or grid demands a pulsating (2×f) instantaneous power as produced by the sinusoidal voltage and current. Most topologies use a large electrolytic capacitor (≥1000μF) placed at the input terminals of the inverter for power decoupling, which are known to be one of the main limits regarding volume and service life in DG systems. For multiple-stage inverters with intermediate dc-link, can waive the use of bulky electrolytic capacitor for intermediate dc filtering.

B. Grid-Connected and Stand-Alone Applications: Inverters for grid-connected and stand-alone systems have different requirements regarding the power flow direction, load characteristic, and system grounding. Normally, the power flow in a grid-connected system is always in the direction from the energy source to the grid; therefore, a unidirectional inverter can be used. For stand-alone systems with reactive loads, the inverters have to be tolerant of load-fed reactive current and transients by providing effective paths to the reactive energy. This could lead to an inverter with simple feedback diodes, an inverter with soft-switched techniques, or a controlled bidirectional inverter with active switches. Controlled bidirectional inverters can be also useful in the case of grid interconnection with a local load, where the power flow is reversed from the grid to charge the intermediate batteries occasionally when the DG resource is scarce and the batteries are exhausted.

C. Grounding: Grounding is necessary when considering maintenance safety, lightning protection, electromagnetic coupling (EMC) diminishment, and electromagnetic pulses (EMP) protection. Above certain dc voltage level, e.g., 100 V, the DG resource is required earth-grounded. In the meantime, a single-phase inverter with line-to-neutral grid interconnection also has one terminal to be grounded. In such a case, the DG inverter has to operate normally under the "dual-grounding" circumstance. Topologies with physical isolation between DG resource and grid have no problems with the dual-grounding requirement. But most of the non-isolated topologies cannot meet this requirement, thereby possibly losing the grid-connected opportunities. Nevertheless, still a couple of non-isolated topologies can be operated with dual grounding. Such topologies are given in [12] & [14].

V. CONCLUSION

In this paper the development of PV inverter technology with larger and darker areas indicating increasing importance of the specific inverter type is described. Although the string and multi-string concept has established itself as a popular PV system concept there is no obvious trend noticeable towards a particular topology: The market share ratio of transformer less inverters versus inverters with transformer has remained constant over the last two years. Amongst the inverters with transformer, line frequency transformer topologies are far more common, but the number of manufacturers offering inverters with high frequency transformer has increased within the last three years and their market share is expected to rise. Developments in the area of standards, particularly in the requirements for safety in PV arrays will in the future affect decisions on preferred topologies.

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