A Comprehensive Review of Inverter Standards and Topologies for Grid-Connected Solar PV Systems

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***Abstract* — The demand for renewable resources is fast expanding as a result of environmental concerns and the necessity for electricity. Solar photovoltaic energy is presently one of the most widely used and renewable energy sources on the planet. An inverter is a crucial component in grid-connected PV systems. This study focuses on inverter standards for grid-connected PV systems, as well as various inverter topologies for connecting PV panels to a three-phase or single-phase grid, as well as their benefits and drawbacks. This study examines several converter topologies used in inverters and compares them based on their efficiency, energy harvesting, cost, shading impact, and dependability.**

***Keywords*— central inverter, string inverter, multi-string inverter, microinverter**

I. INTRODUCTION

Conventional energy resources meet the majority of the world's current energy needs. These materials have limited storage on Earth. Pollution, CO2 emissions, and global warming all have a negative impact on the environment. As a result, renewable energy sources are becoming more popular in today's society. Solar energy is the most popular renewable energy option due to its availability as a source. Technical advancements in solar energy systems make them practical for use in a variety of applications. Solar photovoltaic (PV) is primarily used to convert solar energy into electrical energy; it may be utilized for both small-scale and large-scale power production. Solar photovoltaic technology is becoming more affordable as semiconductor technology advances. Furthermore, advances in power electronics enable high-efficiency energy generation and direct power delivery to the grid. Grid connection is required because PV electricity is more efficiently used and more energy is gathered. Eliminating the use of batteries in a grid-connected PV system has become more cost effective and requires less maintenance.

Figure 1 depicts a block diagram of a typical grid-connected PV system, which includes PV panels from which DC power is generated and subsequently converted or boosted to high voltage DC using a DC-DC converter. This high DC voltage is transformed to AC by an inverter, which is then supplied into a single or three phase grid. The control circuit is utilized to provide the required output from the converter and inverter based on the grid needs. Maximum power point tracking is also provided, which is necessary for maximum energy harvesting via different control strategies.

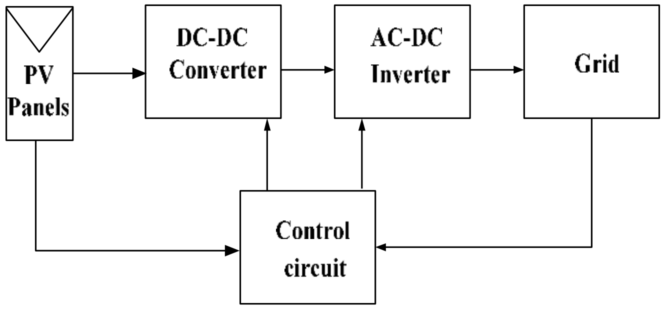

Fig.1. Block diagram of typical grid connected PV systems

Inverters are the main component of grid connected PV systems. It is a power electronic converter which converts DC power from panels into AC power as compatible to grid. There are three main inverter topologies according to their architecture are central inverter, string/multi-string inverter and module integrated microinverter. Central inverter topologies is mostly preferred for large scale generation and it has centralized inverter and common MPPT for PV array (series-parallel connection of PV modules). String inverter topology is reduced version of central inverter, some number of modules are connected in series (string) and inverter is connected to that string is called as string inverter. In which each string has its own MPPT. Multi-string topology is evolution in string inverter for larger system in which strings have their own DC-DC converter and these strings are connected to common inverter and finally the module integrated microinverter in which each PV modules has its own inverter and individual MPPT.[1,2,3]

II. STANDARDS OF INVERTERS FOR GRID CONNECTED PV SYSTEM

To improve reliability of the system the connection of inverter with both grid and PV panels should satisfy the PV systems standards, the main purpose of the inverter is to supply sinusoidal current to the grid. The standard defined by the authorities about PV installation and requirement for the performance of PV converters. Standards of inverter for grid connection are continuously defined due to fast development in PV systems. These standards are ruled by national and international committees like International Electro-Technical commission (IEC) and International Standards of IEEE. When PV is connected to grid through inverter some important terms like total harmonic distortion, DC current injection, galvanic isolation, anti islanding detection and voltage, frequency ranges for uninterrupted operation must be in specified limits according to standards. [4]

A. Total Harmonic Distortion (THD)

According to the standards of IEEE 1547 and IEC 61727 the THD should not be exceed 5% and the harmonic content of injected current should be minimized. The standards also have limitation to DC current injection whose maximum limit is 1 % according to IEC 61727 [6] and 0.5% according to IEEE 1547 standards [5]. THD of the injected current can be reduced by employing soft computing methods for improvement in switching modulation technique of the inverter.

B. Anti Islanding detection

Anti-islanding detection is very important for interrupting the inverter from injecting power to grid when fault occurs on grid side. There is hazardous effect of islanding condition on equipment of the system, so it must have anti-islanding detection. According to IEEE 1547 and IEC 61727 standards the distributed generation like PV systems should not tolerate islanding condition which can be identified and immediately isolate within 2 seconds. Various techniques are used for detection of islanding conditions.

C. Galvanic isolation

While considering the safety issues the galvanic isolation is most important requirement in the PV systems. The capacitance between the ground metallic plate and PV cells causes leakage ground current in absence of galvanic isolation. It helps to reduce leakage current between PV source and grid. According to national electrical code (NEC) galvanic isolation should be provided in PV system above 50V. Also it gives advantage is that if the fault occurs on any side does not affect other side of grid connected PV system.[4,6]

TABLE I. STANDARDS FOR GRID CONNECTED PV SYSTEM [5,6]

Parameters	IEC 61727	IEEE 1547
THD	< 5%	< 5%
Power factor	0.90	-
DC current injection	Less than 1% of rated output current	Less than 0.5% of rated output current
Voltage range for normal operation	85% - 110%	88% - 110%
Frequency range for normal operation	49Hz to 51Hz	59.3 Hz to 60.5Hz

III. INVERTER TOPOLOGIES FOR GRID CONNECTED PV SYSTEM

There are different inverter topologies used for single phase or three phase grid connected PV systems like central inverter, string inverter, multi-string inverter, and module integrated microinverter according to their architecture or arrangement of PV modules interface with inverter and grid.

A. Grid Connected Centralized Inverters

Central inverter system consist of the number of panels which are connected in series to form strings and these strings are connected in parallel by using string diode to form a larger system i.e series-parallel connection of PV panels as shown in Fig. 2. The single centralized inverter is connected to this arrangement of PV panels. The centralized inverter offer a unique solution to the three phase high power PV plant on large scale (up to 1 MW). It is mainly because this system is robust and easy structure with convenient operation. The centralized inverter technology has certain limitation such as using DC cable of high voltage between PV panels and inverter, mismatch losses between PV modules, use of high rating bulky electrolyte capacitor which reduces the life span of inverter. Central inverter are bulky, heavy, difficult to install, having poor power factor, high harmonic content in output AC current, non flexible design and difficulties in integrating the system in future. The main disadvantage of this inverter system is the absence of MPPT to each PV module. If the partial shading or clouding effect occurs on some PV modules it affects the overall performance of the PV system and power generation get reduced. Due to the above drawbacks, the efficiency of overall system decreases which is promoting the development of other inverter topologies.[7,8]

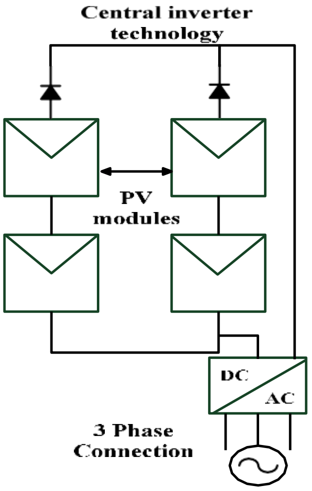

Fig. 2. Grid connected centralized inverter system [1]

i. Three Phase Three-Level Boost Converter Based Centralized Inverter

In this topology grid connected three phase photovoltaic system consist of PV array, three-level boost dc-dc converter and three phase inverter as shown in Fig.3. The three level boost converter step-up the DC voltage from PV array and also perform the MPPT operation, this step-up DC voltage is regulated by three phase inverter and convert it into AC and supply to the grid. Also there is provision in inverter to step down the voltage according to the requirement of the grid thus there is a wide range of voltages due to the step up/down function of the power converter. In high voltage application the three level boost converter have some merits such as it reduces reverse recovery losses of the diode, reduces switching losses and reduction in the rating of the switches(IGBT) which is half of the conventional boost converter as well as the rating of diode is halved. So there is reduction in cost and the operation becomes faster than conventional boost converter. [9]

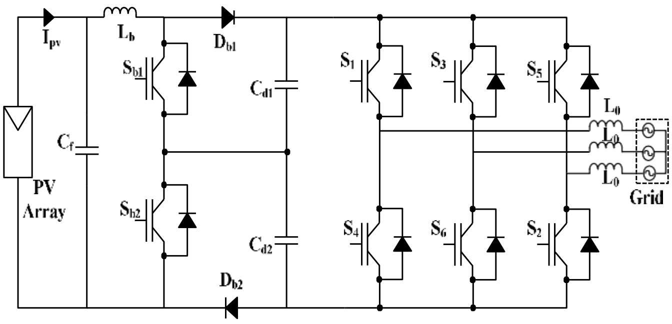

Fig 3. Three level boost converter for three phase central inverter system [9]

B. Grid Connected String Inverters and Multi-String Inverter

The limitations of central inverter system are partially overcome by the string inverter topology. As shown in Fig. 4 the string inverter system consists of number of panels connected in series to form a string and the inverter is attached to that string feeding AC power to the grid. As the single string is connected to a inverter the power rating of inverter is low up to 5kW. The MPPT is attached to a each string gives more accurate maximum power point operation than centralized inverter system. Therefore the partial shading or clouding effect is somewhat reduces. The energy harvesting to the grid is more in this system, losses in string diode is minimized, the size of electrolyte capacitor is reduced hence, the life span of inverter is increases. Efficiency of string inverter is more than that of central inverter topology.

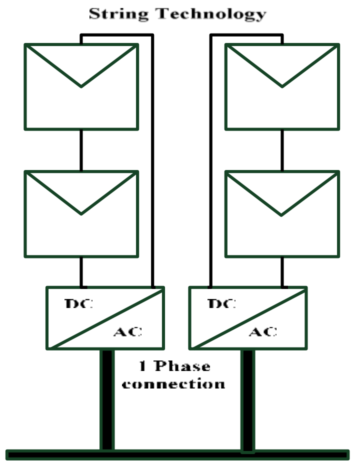

Fig. 4. String inverter technology [1]

But there is still drawbacks such as shading or clouding effect, if the shading occurs on one of the modules of string the whole performance of that PV string get reduces so energy harvesting is less in string inverter topology. The string inverter system has low power rating which for development in string inverter to large power rating system called as multistring inverter topology.[2,3]

The multi-string inverter topology has increased the power scale (level) and retained the string inverter advantages with respect to centralized inverter system. The high rating three phase power can be generated and harvested in three phase grid. The multi-string system consist of the low power DC-DC converters in each string with their own MPPT, which are connected to the inverter via common DC bus and supply power to grid as shown in Fig. 5. The integration of the multi-string inverter system is possible by adding same rating PV string with their DC-DC converter and connected to same inverter through common DC bus. The energy harvesting of the multi-string inverter more than central inverter and provide single or three phase supply according to number of strings which are connected in the system. Advantages and the limitations of the multistring inverter are same as that of the string inverter topology though it is large scale system.[3,8]

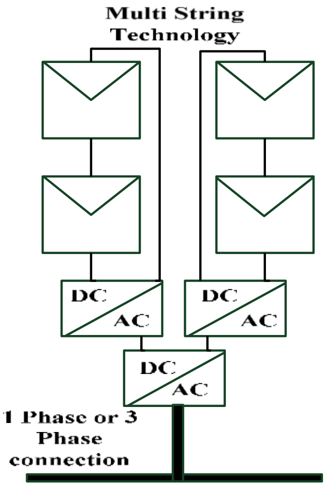

Fig. 5. Multi-string inverter technology[1]

i. Multi String Five-Level Inverter Topology

Fig.6 shows the multi-string five level inverter. It consist of three strings of PV panels each string has its separate DC-DC boost converter. These DC-DC converters are attached to same DC bus. Three PV strings are interface with full bridge inverter through DC-DC boost converter and common DC bus. This DC-DC converter are connected because it extract maximum power point of each string independently and step up the inverter's output voltage so it can synchronize with grid voltage to ensure flow of power from PV panel into utility grid. The PWM control technique is used for giving switching pulse to the switches for producing five level output voltage such that THD of this multi-string five level inverter is very much less than conventional converter topologies.[10]

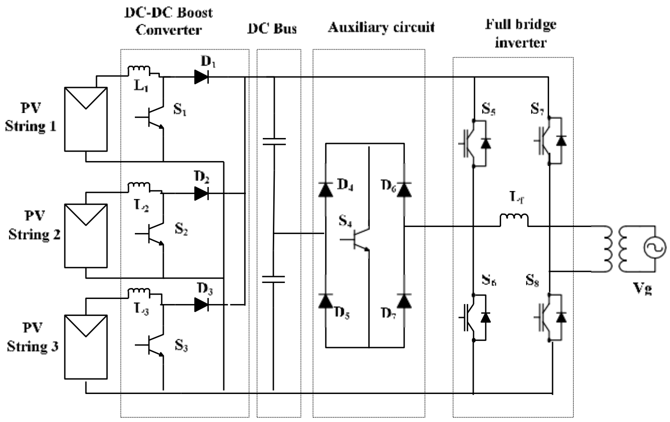

Fig 6. Multistring five level inverter[10]

ii. Cascaded multilevel inverter for string topology

Cascaded multilevel inverter is reliable as compared to other multilevel inverter. This topology consist of series connection of *n* number of H bridge inverters as shown in Fig.7. String of PV panels gives DC voltage to DC link and DC/AC inverter produces output voltage with *n* number of levels. This topology produces the high quality voltage waveform with the reduction in harmonics of output current so as to reduce use of filters. The advantage of this topology is that semiconductor devices used in it having low rating than conventional multilevel topologies hence it becomes cost effective and efficient. [11]

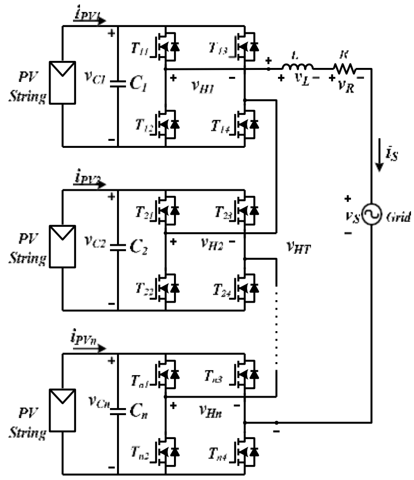

Fig.. 7. Cascaded multilevel inverter for string topology[11]

C. Grid Connected Micro-Inverters

Microinverter topology is the development in the inverter architecture topologies to overcome the losses and drawbacks of the centralized and string inverter system. As shown in Fig. 8, the microinverter topology consist of the module integrated inverter means each module has its own low rated, small size inverter with separate MPPT for each module, so power is supplied to the grid directly through this microinverter. Main advantage microinverter system is to reduce or eliminate the shading and clouding effect in the PV systems. In this topology if partial shading is occurs on one module it affects the performance of only that module and performance of the other modules did not get affected.

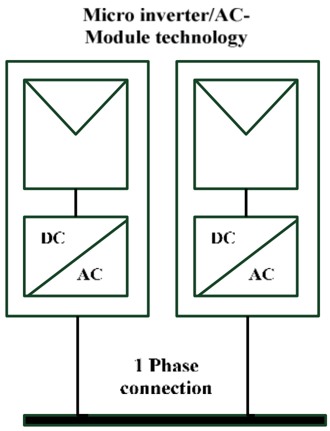

Fig. 8. Module integrated microinverter technology[1]

It also gives more accuracy in MPP operation because each module has its separate MPPT, removing mismatch losses between PV modules. Hence, the energy harvesting to grid increases as compared to the central and string inverter system because of it increasing efficiency of the system. Microinverter topology eliminates the use of DC cables and requirement of the electrolytic capacitor due to which the maintenance becomes less and lifespan of the inverter increases (approx. upto 25 years). Design of the microinverter is flexible and compact. It is like 'Plug-n-Play' device which can be install and operate easily even by a person without any knowledge or expertise in the electrical or PV installation. The integration of system is very simple by adding modules with their inverter and connected to grid. There are some disadvantages such as high installation cost, complex circuit design but the reliability, compact feasible design, maximum energy supplied, long life, low maintenance, possibility of expansion of PV system in future made microinverter topology more trusted and efficient in small and medium scale grid connected PV systems. [2,8]

i. Boost Half Bridge Converter Based Micro-Inverter

Fig. 9 shows the grid connected PV system with boost half bridge microinverter topology, which has two power conversion stages. At front stage there is a DC-DC converter in which output capacitor is split into two separate capacitors C_1 and C_2. L_{in} and C_{in} are boost inductor and input capacitor respectively. The two output capacitor and two power MOSFET switches are connected to boost transformer having turns ratio 1:n and L_s is leakage inductance of primary winding. Two capacitors C_3 and C_4 with voltage doubler circuit formed by two diodes (D_1, D_2) are connected to secondary of transformer and give boost DC voltage to DC– AC conversion stage. Where the full bridge inverter consists of four MOSFET switches convert the boost DC voltage into AC and supplied to the grid. LCL Filter is used to reduce harmonics injected to grid. Operation of both conventional and half bridge boost converter is same but galvanic isolation and high step up ratio are an added feature of the boost half bridge, which gives fault protection and high voltage boosting capacity. Also this topology has simple circuit, number of semiconductor devices are less hence cost is reduced due to which system becomes reliable. [12]

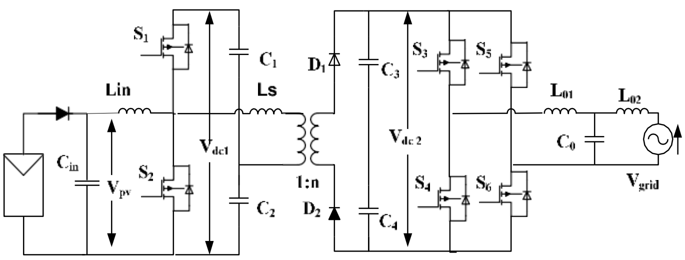

Fig. 9. Boost half bridge converter based micro inverter topology[12]

ii. Interleaved Flyback Based Micro-Inverter

The microinverter based on interleaved flyback converter topology as shown in Fig. 10. In front stage voltage boost, MPPT, output voltage shaping of converter are carried out. The two flyback converters interleaving each other to form a DC-DC converter which is used to prevent high frequency noise get back to the source. The S_1, S_2 are primary switches having PWM function and diodes D_1&D_2 used for reducing reverse recovery losses. Thus output of the interleaved flyback converter is unfolded to AC by using full bridge inverter having four power MOSFET S_{H1}, S_{H2}, S_{L1}, S_{L2}. Switch S_{H2} and S_{L2} switch on during positive half cycle, S_{H2} and S_{H1} is on during negative half cycle and supply AC current to the grid. The interleaved flyback topology has simple closed loop, less circuitry and low cost making it reliable for the application of microinverter system.[13]

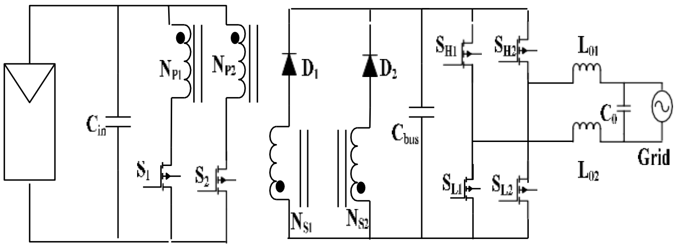

Fig.10. Interleaved flyback micro inverter topology [13]

iii. Push-Pull Converter Based Micro-Inverter

The push-pull based single stage microinverter topology is as shown in Fig. 11. This converter is constructed by replacing output rectifier of conventional push-pull converter with back to back connected IGBTs, which forms the set of bidirectional switches connected to push pull transformer. The output from transformer is high frequency square wave, which can be unfolded using these switches and converted AC is provided to the grid. This push-pull converter topology achieves the requirements of micro inverter such as elimination of high rating electrolyte capacitor, single stage power conversion & less reactive components. This topology also reduces the electromagnetic noise and have the low semiconductor stress. [14]

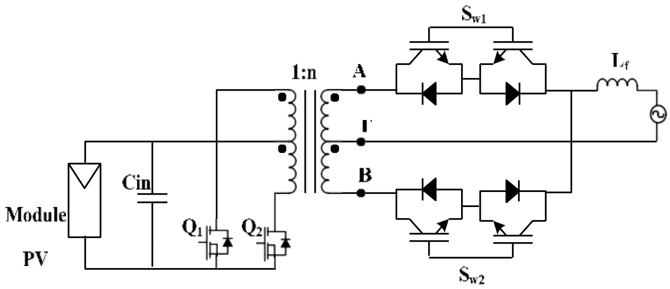

Fig. 11. Single stage push-pull converter topology[14]

IV. Comparison Between the PV Inverter Topologies

Comparison between the grid connected PV inverter topology are described in TABLE II in terms of effect of shading, cost, losses, efficiency, reliability, total energy harvesting and some other aspects.

TABLE II. Comparison of Inverter Topologies

Parameters	**Central inverter**	**String / multi string inverter**	**Microinverter**
Phases	3 phase	1 phase /3 phase	1 phase
Energy harvesting	Less	More than central	Greater than both
Shading effect	Shading on one module affect overall Performance	Shading on one module affect performance of modules connected to that string	Shading on one module affect performance of only that module
Rating	High (>2kW)	Medium(upto 2 kW)	Low (upto 400 W)
Scale	Large scale	Medium /large scale	Small scale
Installation cost	Low	More than central	Higher than both
Maintenance cost	High	Less than central	Very low
Efficiency	Average	More than central	Greater than both
Inverter arrangement	Single inverter for all modules (plant oriented)	Inverter attached to each string	Inverter attached to each module

V. Conclusion

This paper discusses the inverter standards of PV systems that must be fulfill by the inverter used in grid connected PV systems focusing on THD (<5%), DC current injection, Anti- islanding detection standards. It also discusses the various inverter topologies used in grid connected PV system and their converter topologies. The conventional topology in which large number of PV modules connected to grid through centralized inverter has many limitations which results in the development of small scale string topologies. From this, the multistring topology is developed having large scale system with the advantages of string topology is achieved. The new module integrated microinverter topology has used in grid connected PV system widely because of its merits over the other topologies like reducing shading effect, more energy harvesting, reduce miss match losses between PV panels, compact feasible design with plug-n-play operation, long life span and low maintenance makes it more reliable and efficient.

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