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THE INTEGRATION TECHNOLOGIES OF PHOTOVOLTAIC POWER TO THE UTILITY GRID

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Abstract- *The Photovoltaic renewable energy system may be one of the promising solutions to ease the existing electricity crisis in the world if its integration to the grid is made technically feasible, cost effective and sustainable. Design of converters is the pivotal issue for the quality integration of photovoltaic systems to the utility grid. Generally power converters consist of two stages, one of them is dc/dc booster converter, and the other one is PWM inverter. This paper aims to give a comprehensive survey on converters used for grid connected photovoltaic (PV) power system, especially on novel multilevel inverter topologies developed recently. A critical review on maximum power point tracking (MPPT) method is also presented to get quick idea on this technology.*

Keywords: *Photovoltaic (PV) Renewable Energy Systems, Multilevel Inverter Topologies, Maximum Power Point (MPPT), Pulse Width Modulation (PWM)*

1. INTRODUCTION

Photovoltaic power generation using solar cells that can convert solar light energy directly to DC electricity promises to be a clean, widely applicable renewable energy source. Researchers have shown great interest on photovoltaic (PV) technology over the past decades. Advancement in cell efficiency and system reliability has given wide acceptance of PV power technology for both standalone and grid interactive power generation. Sustainable growth of photovoltaic power generation throughout the world is also reducing dependence and pressure on fossil fuel considerably. According to the renewable energy unit of European Commission, the capacity of installed grid connected PV grew at an average rate of 37% per year over the years 2002-2008 [1]. At the end of 2010, the installed capacity in the USA was nearly 11,000 megawatts (MW) and the worldwide installed capacity was over 16,000 MW (see fig. 1). Photovoltaic renewable energy is recognized worldwide as a cost-effective, environmentally friendly solution to energy shortages. The major technical challenge lies on the development of appropriate converter technology and control philosophy for connecting PV arrays to the grid so that DC voltage from the PV arrays is converted to grid's AC voltage of appropriate magnitude and frequency [1]. Several different semiconductor devices, such as MOSFETs and IGBTs are used in the power stage of the inverter.

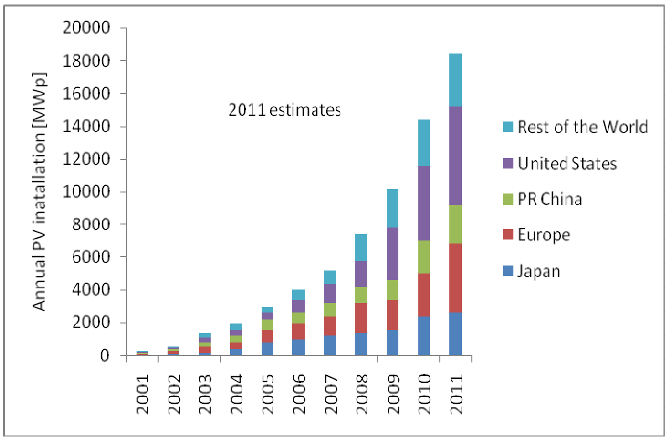


Fig. 1: Grid Connected Photovoltaic Installations [6]

A photovoltaic array is a group of photovoltaic modules which are put together to generate more electricity. A PV array may consist of one module to thousands of modules. In figure 2 it is shown that each module consists of thirty six PV cell connected in series. The output of the array may vary from a few watts to tens of megawatts depending on the number and output of the modules. To extract energy from a PV array and supply it to the utility grid the following three criteria have to convert dc voltage available from photovoltaic array into ac voltage, and then to boost the voltage if the PV array voltage is lower than the grid voltage and 3) To reduce harmonics from the current and/or voltage waveform as well as phase synchronisation of the inverter output voltage with that of the utility grid to be connected.

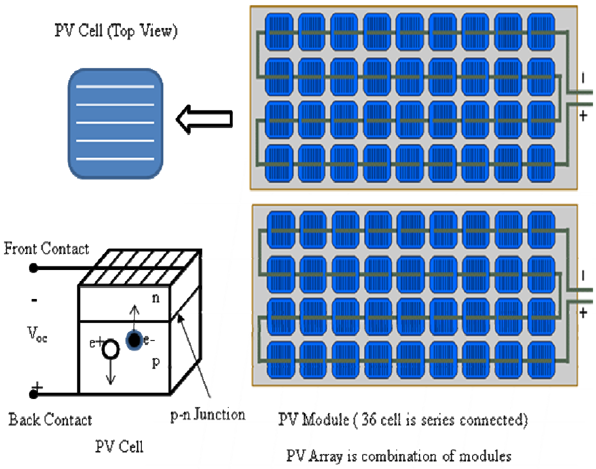
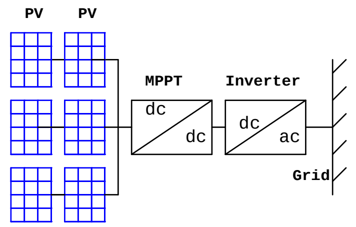
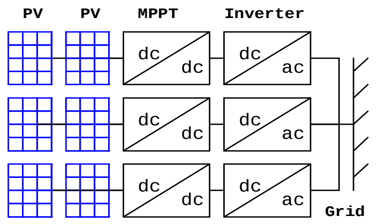
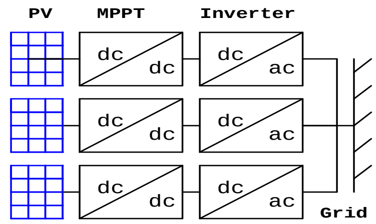


Fig. 2: PV cell, PV module and PV array

According to [2], [3] PCS system can be divided broadly in three categories: 1) The Central PCS, 2) The String PCS, and 3) The Modularized PCS. In the Central PCS, PV modules are connected in several parallel strings which interface to a central inverter. In the String PCS, each string has a separate inverter and a maximum power point tracker (MPPT). While in the Modularized PCS, each module has its own inverter and MPPT. The main features of these topologies are summarised in Table 1.

Table 1: Overall PCS Systems

Type	Central PCS	String PCS	Modularized PCS
Circuit topology			
Features	(1)High voltage and high current in dc bus, (2) Large mismatch losses of electrical arc in DC wiring, (3)Higher current harmonics and low quality, (4) Used in large scale (>5kW) PV system integrated to grid.	(1) High voltage and low current in dc bus, cost reduction and improvement by using similar components, (2) Easier to find fault, (3) Higher overall efficiency than Central topology (4) Used in medium scale (2-3kW) PV system.	(1) Low voltage and low current in dc bus, (2) Low mismatch losses and have flexible design for expansion, (3) Difficulties in replacement in case of inverter faults, (4) Used in small scale (<2kW) PV system.

2. INVERTER TOPOLOGIES

There are various types of inverter topologies. These topologies can be broadly categories in the following two ways: (1) Inverters with transformer and (2) Transformer less inverter. The first one can be of several types like, dc/ac with low frequency transformer, dc/ac with high frequency transformer, flyback inverter. There are also a numerous types of transformer less inverter, such as, single stage dc/ac, dc/ac with dc/dc booster, dc/ac with bidirectional switches, cascaded inverter, and single stage half bridge with dc/ac. Since these topologies are already reviewed in [3]–[5], so further details are not given here. Rather a comprehensive review on multilevel inverter topologies as well as control philosophies of maximum power point tracking (MPPT) is presented in this paper.

3. RECENT DEVELOPMENT AND TRENDS

Presently, the grid connected PV inverters have the input DC voltage higher than ever. For this reason, the system has become easier to install. The input DC voltage may be still higher if multilevel inverter topology is used and thus eliminate the need of transformer for grid integration. Moreover, to obtain a quality output voltage or a current waveform from ordinary two level inverters with a minimum amount of ripple content, they require high-switching frequency along with various pulse-width modulation strategies. In high-power and high-voltage applications, these two-level inverters have some limitations in operating at high frequency mainly due to switching losses and constraints of device ratings. Multilevel converters have been mainly used in medium or high power system applications. Due to the limitations of the currently available power semiconductor technology, a multilevel concept is usually a unique alternative because it is based on low- frequency switching and provides voltage and/or current sharing between the power semiconductors. So, research on this topology is increasing and the progress is remarkable. There are a number of multilevel inverter topologies. Among them the most popular multilevel topologies along with their main features are discussed here.

3.1 Grid-tied Inverter

Single-phase, 11-level, cascaded topology is a real-time control system platform to implement MPPT. In figure 3 A novel SPWM scheme is proposed to be used with the solar panels that can account for voltage profile fluctuations among the panels during the day. Unlike diode clamped multilevel converters [6], it does not require any of the H bridges to be switched in a determined sequence thus enabling it to equalize the power transferred from the individual panels. Instead of sensing the individual panel voltages traditionally, the MPPT algorithm determines the optimal point of operation of the panel by calculating the output power and phase angle variation. The authors suggest that future work should use DSP platform to increase switching frequency and reduce filter requirement [7].

3.2 Diode Clamp Inverter

Diode clamped topology, provides seven voltage levels, thus staircase waveforms can be produced, which approach the sinusoidal waveform with low harmonic distortion, thus reducing filter requirement, The proposed topology is better because of the significant reduction in the total VA ratings of the clamping diodes and in the total voltage rating of the voltage-splitting capacitors. [9]. Among many option one is shown as in figure 3. There is no need of transformer in this topology and it is beneficial for large systems in terms of cost and efficiency.

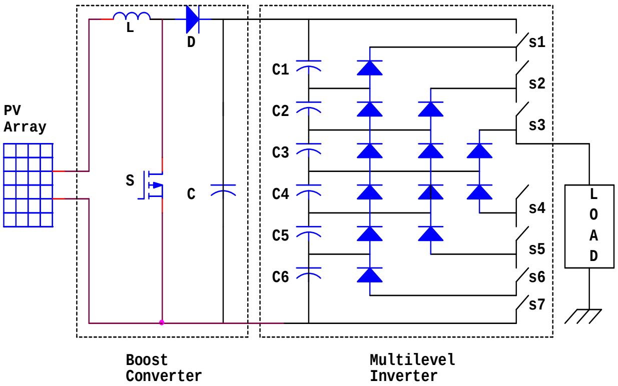


Fig. 3: Diode Clamp Multilevel Inverter

3.3 Single-Phase Photovoltaic Grid-Connection with Cascaded H-Bridge

To overcome partial shading when the PV operates under non-uniform irradiation the cascaded topology H bridge topology is proposed in [10]. The schematic of the system is shown in figure 4. Using this topology, PV modules are divided by the number of H-bridge modules. Each DC voltage is stably controlled to their maximum power points by dedicated and individual MPPT algorithm. In order to achieve the individual MPPT, the each DC link voltage loop is designed to stabilize the current loop closed system. For the unity power factor the PI current controller with the duty ratio feed-forward compensation method is employed.

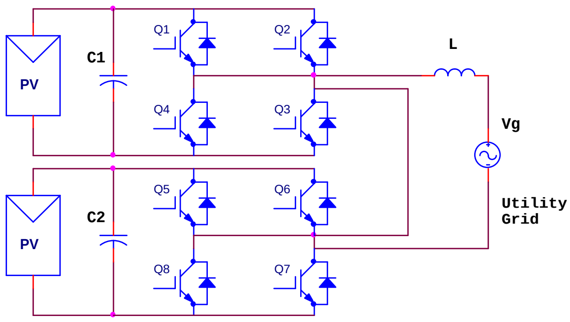


Fig. 4: H-Bridge Multilevel Inverter

3.4 Grid-Connected Photovoltaic Systems with Boost Current Inverter

The proposed system comprises of a dc-to-dc Boost converter as in figure 5, cascaded by a current-source inverter.

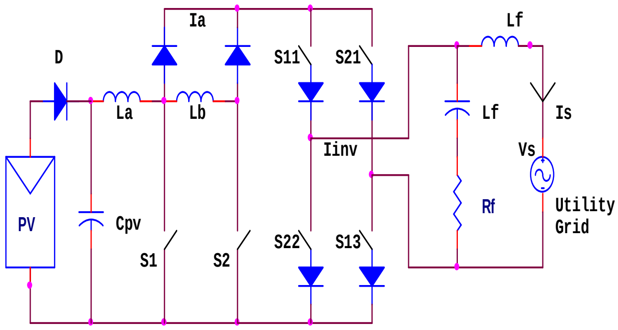


Fig. 5: Boost Current Multilevel Inverter

The modulation of the output current is performed by the dc-to-dc converter. The current source, in the input of the dc-to-dc converter, is composed by the PV array connected to an inductive filter. It allows a high power factor operation, shows good efficiency and power quality and has a natural short-circuit protection and a balanced current sharing among the switches of the dc/dc converter [10]. Apart from the topologies presented in Table 2, there are a number of inventions presented in [11]–[12] in the multilevel inverter family. In [13], the inverter generates almost harmonic free output, quality power and decreased energy loss. The topology proposed in [14] has the advantage of operating at fundamental frequency switching and better THD.

4. Market shares of different inverter topologies

An indication of market share for different inverter topologies can be gained from the market surveys on PV system, which include information on inverter type used. Figure 6 shows the result of the evolution of the 2008 survey [15]. It is interesting to mention that the high and growing share of cascaded bridge PV inverter (over 47%). Also the share of topologies with multilevel inverters (below 24%) and diode clamp inverters (17%). Only a selection of key PV inverter manufacturers are represented in the PV system market survey and consequently not all available inverter topologies are covered.

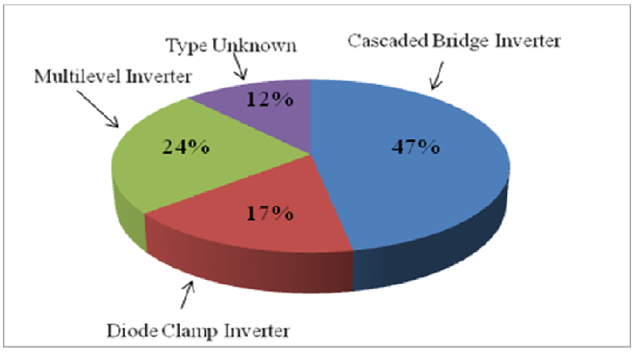


Fig. 6: Market Shares of Different Inverter Topologies

5. MAXIMUM POWER POINT TRACKING METHODS

The power supplied by PV arrays depends on the irradiation intensity, temperature, and PV array voltage. Usually, the PV output voltage changes with temperature, while the PV output current changes mainly with insulation as shown in figure 7.

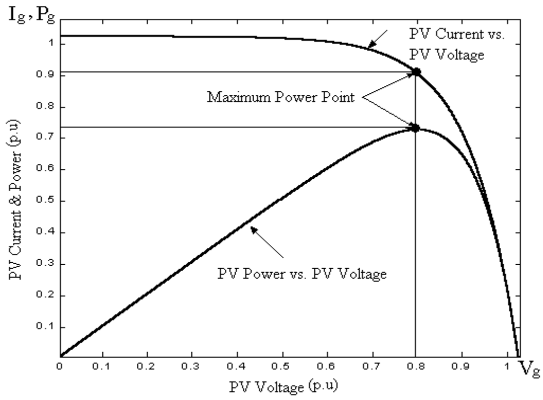


Fig. 7: (I-V) and (P-V) characteristics of a PV array [16].

The photovoltaic system displays an inherently nonlinear current-voltage (I-V) relationship, requiring an online search and identification of the optimal maximum operating power point. MPPT controller is a power electronic DC/DC chopper or DC/AC inverter system inserted between the PV array and its electric load to achieve the optimum characteristic matching PV array is able to deliver maximum available power that is also necessary to maximize the photovoltaic energy utilization. The use of MPPT can make full use of the system capacity and thus reducing the cost of the system. A number of methods for MPPT have been reported in the literatures [17]. Methods have been classified according to the parameters the use to find MPP. Different MPPT techniques discussed earlier have been summarized in table 2, in terms of their tracking efficiency, cost effectiveness, implementation complexity convergence speed and so on. Major Characteristics of MPPT techniques are sum up to go over the main points at a glance as in table 3. In recent years, numerical techniques are adopted in MPPT. Few applications of this technique are presented in [25], [26]. As the digital signal processing (DSP) technology is being flourished, DSP based control strategy in MPPT is now developing [27]. Fuzzy logic and other artificial intelligence (AI) techniques are also being introduced considerably [28] for MPPT.

6. CONCLUSIONS

The photovoltaic solar power is one of the most attractive alternative energy sources nowadays. The inverter topology of grid connected PV systems is the main barrier to utilize PV power efficiently. This paper has presented a summary of PV power conditioning system inverter topologies and some recent findings on multilevel inverters. The paper also critically reviews the MPPT techniques. Most of the authors address transformer less multilevel grid connected power conditioning system along with incremental conductance algorithm for MPPT. It is hoped that this review paper will be much useful to the new researchers in getting quick idea on research trends and future prospect in this area.

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Table 2: MPPT Methods

Types	Main Features
(1) Look-up table method	Measurement parameters are PV voltage, current, insulation intensity and system temperature. The measured values of the PV generator's voltage and current are compared with those stored in the controlling system, which correspond to the operation at the maximum point, under predetermined climatologically conditions. A PI type controller adjusts the duty cycle of the dc to dc converter; large memory capacity is needed the systems able to perform fast tracking [18].
(2) Voltage based method	Measurement parameter is open circuit voltage. A linear relationship between the open circuit voltage and voltage at MPP, open circuit voltage is measured and voltage at MPP is calculated from it. The system is simple, but interrupted system operation yields power losses. Algorithm response is fast.
(3) Current based method	Measurement parameter is short circuit current. A method similar to the procedure as mentioned in (1) is used in [19]. There is a linear relation between MPP and short circuit current of PV generator. Output terminals should be short circuited to obtain short circuit current.
(4) Perturbation and observe	Here the parameters are PV terminal voltage, current. The P&O MPPT algorithm is used frequently, due to its ease of implementation. It is based on the following criterion: if the operating voltage of the PV array is perturbed in a given direction and if the power drawn from the PV array increases, this means that the operating point has moved toward the MPP and, therefore, the operating voltage must be further perturbed in the same direction.A drawback of MPPT technique is that, at steady state, the operating point oscillates around the MPP giving rise to the waste of som of available energy and the system accuracy is low [20].
(5) MPPT via capacitor identifier	Measurement parameters are capacitor current, PV terminal voltage and current. In this method, the capacitance based on the model reference is estimated, and then the accurate capacitance in any time is obtained. The change in duty ratio is decided by identifying capacitance and increase or decrease in duty ratio is decided by P & O method or incremental conductance method. This method is applicable where more numbers of modules are required [21].
(6) MPPT via Output parameter	Measurement parameters are output voltage and/or current, rather than input voltage and current. The output parameters simplify the MPPT controller. Moreover, using this approach [22], only one out of the two output parameters needs to be sensed. This observation is general and applies regardless of the power stage or the realization of control algorithm. Algorithm response is fast.
(7) Incremental Conductance	Measurement parameters are same as P&O method. The PV array terminal voltage can be adjusted relative to the maximum power operating point voltage by measuring the incremental and instantaneous array conductance. The method offers good performance under the fast changing insulation. High complexity and fast control speed adds to the cost of the total system.

Table 3: Major Characteristics of MPPT techniques

MPPT Technique	True MPPT or not	Dependency on Module	Periodic tuning	Sensing parameters	Complexity	Convergence speed
Look-up table method	Yes	Yes	No	Voltage, current	Low	Low
Voltage based method	Yes	Yes	Yes	Voltage	Low	Medium
Current based method	Yes	Yes	Yes	Current	Medium	Medium
Perturbation and observe	Yes	No	No	Voltage, current	Low	Varies
MPPT via capacitor identifier	No	No	No	Voltage	Medium	Low
MPPT via output parameter	No	No	Yes	Voltage, current	Fast	Low
Incremental Conductance	No	Yes	No	Voltage, current	Medium	Varies