Adaptive Hysteresis Current Controlled Multilevel Inverter for Solar Photovoltaic Applications

K. Punitha [1], Dr. D. Devaraj[1], Dr. S. Sakthivel [2]

[1.] Department of EEE, Kalasalingam University,, Krishnankoil 626125, India
[2.] Department of EEE, PSNA College of Engineering, Dindugal, India
kgpunitha@gmail.com

Abstract: This paper presents a five-level cascaded multilevel inverter controlled by means of an adaptive hysteresis band current controller for photovoltaic (PV) system. Due to increasing the number of levels, the proposed five-level cascaded multilevel inverter further reduces its THD. The solar array is simulated using MATLAB/Simscape software and it is integrated with DC-DC boost converter and single-phase five-level cascaded multilevel inverter controlled by the proposed control strategy. The simulation results show that the proposed controller provides constant switching frequency, reduced harmonics and can reach its steady state quickly compared to the conventional fixed hysteresis controller and standard PWM controller. Also, the proposed five-level cascaded multilevel inverter reduces THD of the output voltage and current. The proposed controller is also implemented Xilinx Spartan 3E FPGA using the Atmel AT90USB2 USB controller on the Basys 2 development board. The simulation and experimental results describe and verify the current control technique for the multilevel inverter.
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Keywords: Adaptive Hysteresis Current Controller, Photovoltaic System, Multilevel Inverter, MPPT.

1. Introduction

The adverse environmental impact and the cost of fossil oil have forced the society to focus on the green and clean energy provided by renewable energy sources especially solar, wind and biomass. Among the various renewable energy sources, solar is an attractive option because of enormous amounts of power available in sunlight. The solar PV system does not only consist of PV panels but also requires some power electronic converters for connecting its output to the existing grid and grid connected loads. The power electronics converter normally used are, DC-DC converter to boost up PV output DC, and DC-AC inverter for AC conversion. The use of power electronic converters introduces new problems like power loss, electromagnetic interference (EMI), thus reducing efficiency, power quality and stability. In view of the above reasons there is a need to introduce a new inverter topology and modified controlled algorithm, aiming at improving the quality of solar energy produced.

The reference paper [2] has proposed multilevel inverter for active filter application. The multilevel inverters are proposed for PV system in [1, 5, 7] but with PWM modulated and frequency modulated controllers. The adaptive hysteresis current controller has been adopted for active filter in [2, 3, 8], for providing constant switching frequency. The control and design of multilevel inverter have significant problems like complexity. Many researchers have found different solutions [11-13]. Few papers proposed fuzzy logic (FL) alone [14-17] and some papers FL in conjunction with sliding mode or a PI controller for AC converters [18-21]. Recently, multilevel inverters have attracted the electrical engineers due to reduce THD. As the number of voltage levels increases in the multilevel converters, the output voltage waveform becomes a staircase wave which approaches a sine waveform with minimum harmonic distortion. Multilevel inverters have been proposed for PV system applications also [22-29].

In the author's knowledge, until now, only a group of researchers has previously addressed the modeling of PV array in Matlab coding, Simulink or PSIM but not using Simscape software tool. This article proposes a Simscape modeled PV array integrated with conventional Perturb and Observe (P & O) MPPT controlled DC-DC boost converter and adaptive hysteresis current controlled DC-AC multilevel inverter and electric grid.

Section II briefs the PV Array Characteristics, Section III deals with PV System Description, Section IV Describes the Adaptive Hysteresis Current Controller for Multilevel PV Inverter, Section V presents the Simulation Results, and Section VI provides the Experimental results and finally Section VII reports Conclusion and references.

2. PV Array and its Characteristics

The most important component that affects the accuracy of the simulation is the PV cell model.

Modeling of PV cell involves the estimation of the I–V and P–V characteristic curves to emulate the real cell under various environmental conditions. The mathematical equations describing the PV model can be divided into four aspects [6]. They are firstly relations between solar cell temperature and ambient temperature, secondly PV short circuit current, thirdly PV open circuit voltage and final expression of the PV cell's I-V relation. The characteristics of the PV cell can be expressed as the following:

$$I = I_{ph} - I_s(e^{\frac{(V+IR_S)}{(NV_{t-1})}} - 1) \qquad (1)$$

In this equation, I_s represents the saturation current of diodes; V_t represents thermal voltage; N represents a quality factor; I_{ph} represents light generated current. The I_{ph} is in proportion to light intensity (I_r). That is,

$$I_{ph} = I_r(\frac{I_{ph0}}{I_{r0}}) \qquad (2)$$

I_{ph0} is the light generated current under standard light intensity (I_{r0}). This is the model of a PV cell. Typical I-V and P-V characteristic curves of the PV cell are shown in fig. 1 (a) and (b).

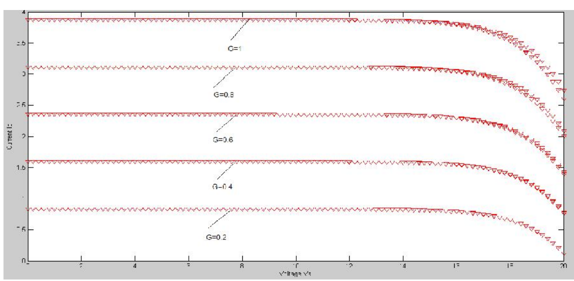


Figure 1. (a). Current Vs Voltage at Irradiant G= 1 W/m^2, 0.8W/m^2, 0.6W/m^2,0.4W/m^2,.2W/m^2

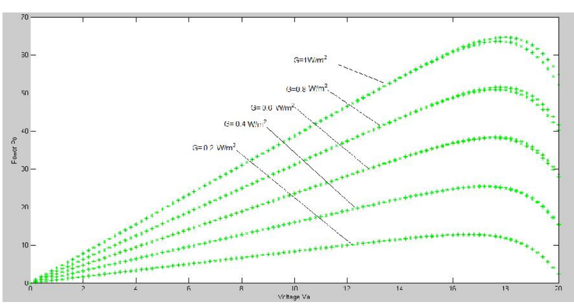


Figure 1(b). Power Vs Voltage at Irradiant G= 1W/m,0.8W/m^2,0.6W/m^2,0.4W/m^2,.2W/m^2

3. PV System Description

Fig. 2 shows the single-phase five-level cascaded multilevel inverter topology connected to PV array via DC-DC boost converter. The DC-DC boost converter is used to track the Maximum Power Point (MPP) of solar array output as well as to step-up the voltage generated by the PV array. The Photovoltaic (PV) cell has an individual operating point where it can provide the highest electrical power, the Maximum Power Point (MPP). The conventional Perturb and Observe (P & O) algorithm is used for MPPT, the details of which are given in Appendix I. In the design of multilevel inverters, higher the number of levels, better the sinusoidal voltage and current waveforms. However, as the number of levels increases, the complexity with the cost of the system also increases in comparison with conventional two-level inverter. From the efficiency and technical point of view, total losses will be lower in a multilevel inverter rather than using a conventional two-level inverter. The multilevel inverter can operate at significantly higher switching frequencies than a conventional inverter, thus allows the use of smaller low-pass filters. The output of the multilevel inverter is interfaced with the electrical grid. The multilevel inverter is controlled by an adaptive hysteresis current controller whose details are given in the next section.

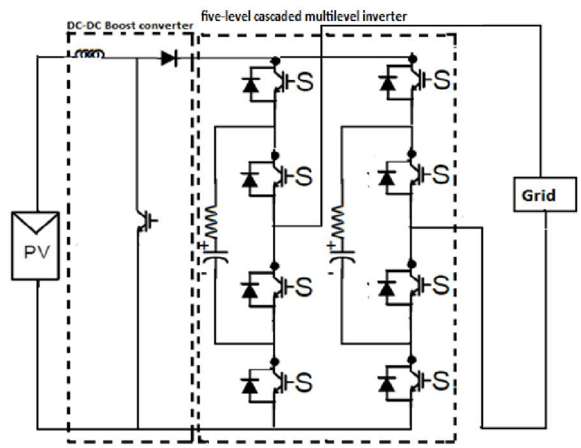
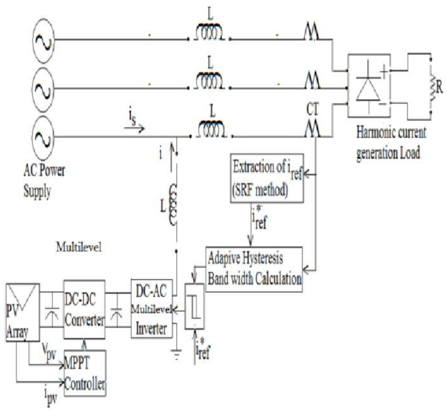


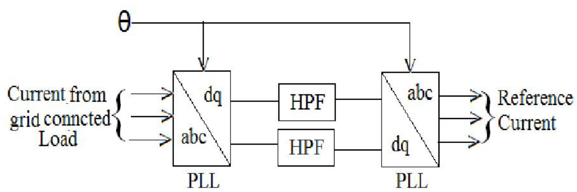
Figure 2. PV Array Connected to a Single-Phase Five-Level Diode-Clamped Multilevel Inverter Topology

4. Adaptive Hysteresis Current Controller for Multilevel PV Inverter

The overall PV system block with its controller is shown in Figure 3 (a). In the adaptive hysteresis controller, the hysteresis band is controlled as a variation of input voltage, output voltage, and slope of the reference current to achieve constant switching frequency at any operating condition. Synchronous Reference Frame (SRF) is used to extract the reference current from the grid connected load current [4] utilized for adaptive hysteresis band calculation. The principle of SRF method is shown in Figure 3(b). In this method the load current is transformed into conventional rotating frame dq. The θ is the transformation angle that represents the angular position of the reference frame. The reference frame is rotating at constant speed synchroning with the three phase AC voltages. To implement this method, a synchronizing system like phase lock loop (PLL) is used. The high pass filter (HPF) is used to eliminate the harmonic content in this method. One of the three phases of reference current is then used for adaptive hysteresis current band calculation. This method is used when the voltages are distorted or unbalanced or sinusoidal current is needed.



(a)



(b)

Figure 3 (a) An Adaptive Hysteresis Current Controller for PV System, (b) SFR Model to Extract Reference Current

The concept of adaptive hysteresis current control has been investigated in reference paper [2]. The five different voltage levels of multilevel inverter are $2V_{dc}$, V_{dc}, 0,-V_{dc} and -$2V_{dc}$. The hysteresis bands of various voltage levels derived are,

$$HB = -\frac{V_{dc}(Lm+V_s)-(Lm+V_s)^2}{2f_c.V_{dc}.L},\ m = \frac{di^*_{ref}}{dt} \tag{3}$$

$$HB = -\frac{V_{dc}(Lm+V_s)-(Lm+V_s)^2}{2f_c.V_{dc}.L},\ m = \frac{di^*_{ref}}{dt} \tag{4}$$

$$HB = -\frac{V_{dc}[5(Lm+V_S)-V_{dc}]-(Lm+V_{dc}+V_S)^2}{2f_c.V_{dc}.L} \tag{5}$$

$$HB = -\frac{V_{dc}(Lm+V_s+V_{dc})-(Lm+V_{dc}+V_s)^2}{2f_c.V_{dc}.L},\ m = \frac{di^*_{ref}}{dt} \tag{6}$$

The slope of the reference current m, the DC link voltage V_{dc}, the grid voltage V_s and the inductance value L are defined in these equations. The hysteresis band size can be determined by a calculation in order to find out a desired switching frequency f_c. The load currents are sensed and compared with respective command currents by hysteresis comparators having a hysteresis band "HB". The output signal of the comparator is used to activate the inverter power switches.

5. Simulation Results and Discussion

The proposed system was simulated using Simulink and Simscape toolbox available in MATLAB. The characteristic of PV array has been obtained from the Simscape modeled system. The Simscape modeled a PV array is again integrated with simulated DC-DC converter, DC-AC inverter and gird. A PV array consisting of 54 PV modules arranged in three phases, where each phase comprises of 18 modules which are connected with nine modules in series and two in parallel. The complete PV array is shown in Figure 4 (a).

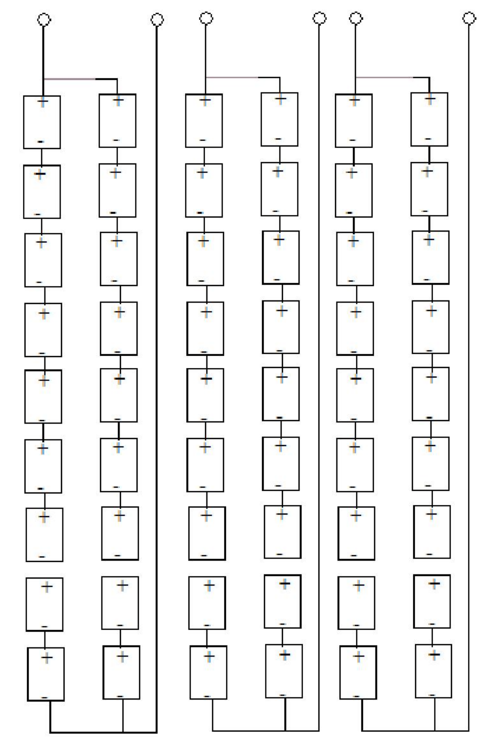


Figure 4 (a). PV Array Configuration of Three Phase System

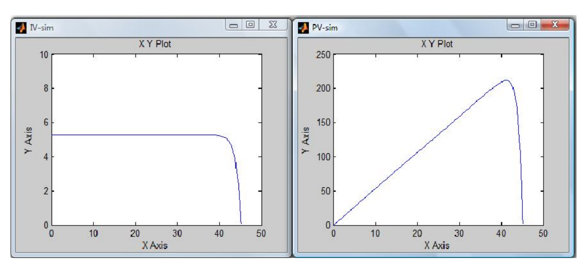


Figure 5 (a). I-V and P-V Characteristics of a PV Module Consisting of 36 PV Cells in Series

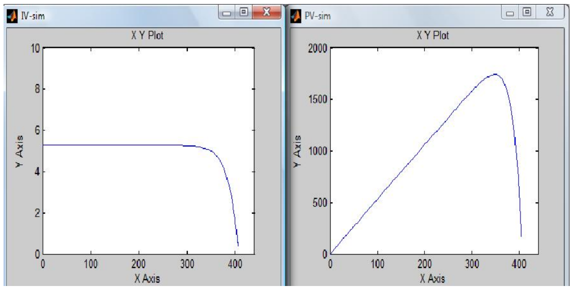


Figure 5(b). I-V and P-V Characteristics of 9 PV Modules in Series

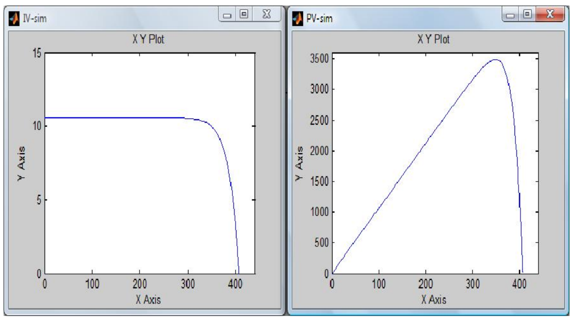


Figure 5(c). I-V and P-V Characteristics of Single Phase (Series Connected 9 PV Modules Parallel with Other 9 PV Modules)

The PV array configuration is constructed in the Simscape MATLAB window whose temperature and irradiations are also described in the software. The insolation level considered is taken as G= 1000W/m^2. I-V and P-V characteristics of single module, 9 series modules and 18 modules (two parallel 9 series) are shown in Figure 5 (a), (b) and (c) respectively.

The proposed adaptive hysteresis current controller was simulated using Simulink, SimPower Systems and Simscape toolbox. The proposed controller is used to produce the output in such a way that the current has low Total Harmonic Distortion and it has a constant switching frequency. Because of increasing the number of levels**,** the proposed five-level cascaded multilevel inverter further reduces its THD. The output voltage of five-level inverter with its THD is shown in Figure 6. Figure 7 (a) shows the input/output current and voltage of the PV system with the adaptive hysteresis current control scheme. The performance of the proposed control algorithm is found to be excellent. The THD in this case is 4.52% as shown in Figure 7(b). In this case the modulation frequency is maintained constant at 5 kHz. The performance of proposed controller was compared with that of standard sine PWM controller and conventional fixed hysteresis current controller in terms of THD and constant switching frequency. The THD of former controller is 4.66% [Figure 8] and later is 6.92% [Figure 9]. The THD and average switching frequency of various controllers are summarized in Table I. It is demonstrated that the proposed adaptive hysteresis current controller generates an output voltage with lesser THD with a constant switching frequency.

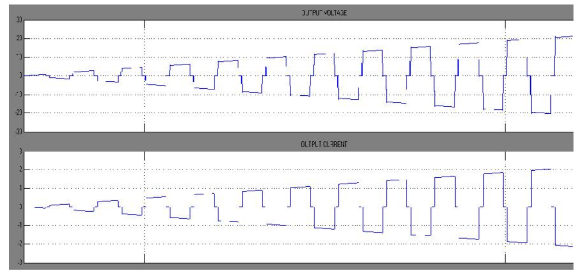


Figure 6(a). Initial Output Voltage and Current of PV Multilevel Inverter

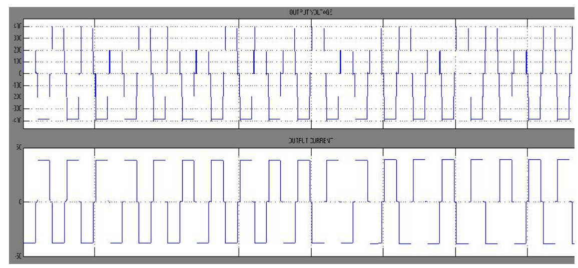


Figure 6(b). Saturated Output Voltage and Current of PV Multilevel Inverter

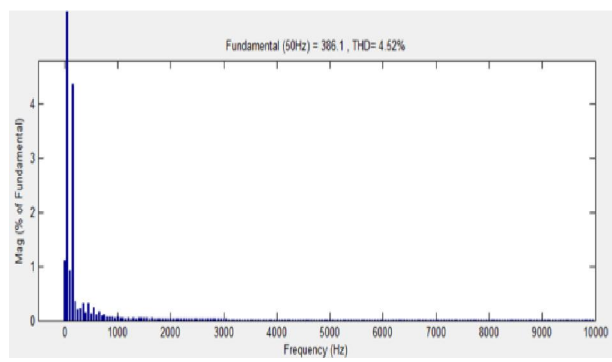


Figure 7(a) THD Level of Adaptive Hysteresis Controller of PV Inverter

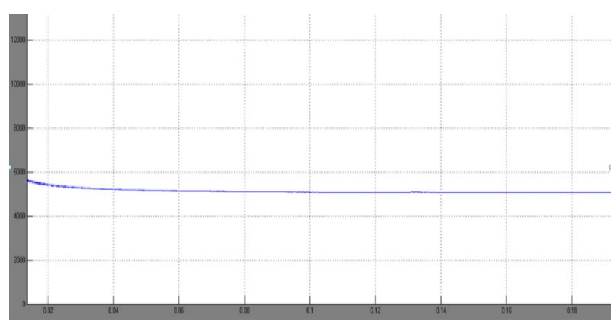


Figure 7(b). Switching Frequency of Adaptive Hysteresis Controller of PV Inverter

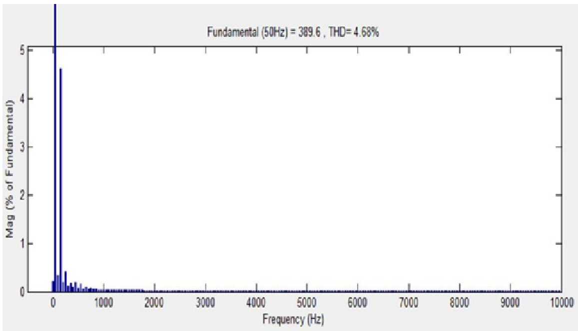


Figure 8 (a) THD level of the Sine PWM Controller of PV Inverter

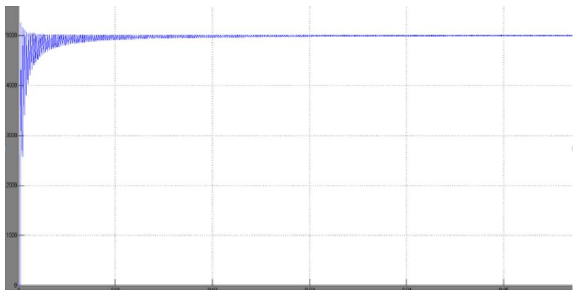


Figure 8(b). Switching Frequency of Sine PWM Controller of PV Inverter

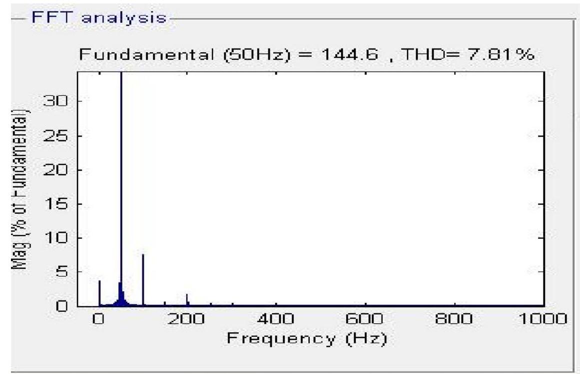


Figure 9(a) THD of Fixed Hysteresis Current Controller of Multilevel Inverter

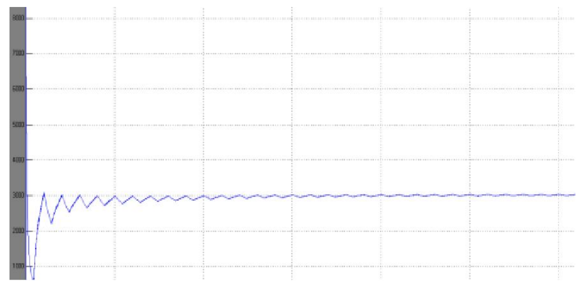


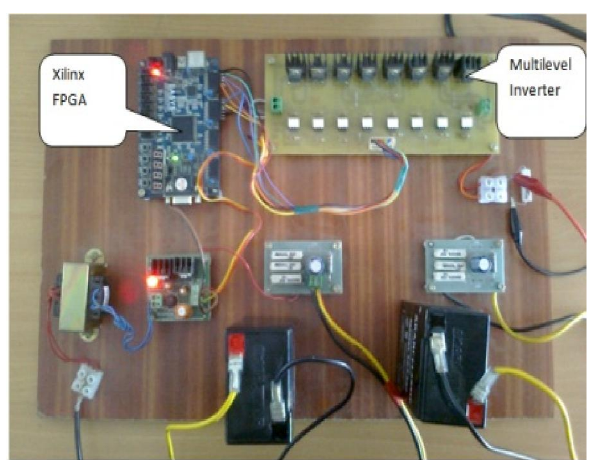
Figure 9(b). Switching Frequency of Fixed Hysteresis Current Controller of Multilevel Inverter

Table 1. Results of Various Techniques

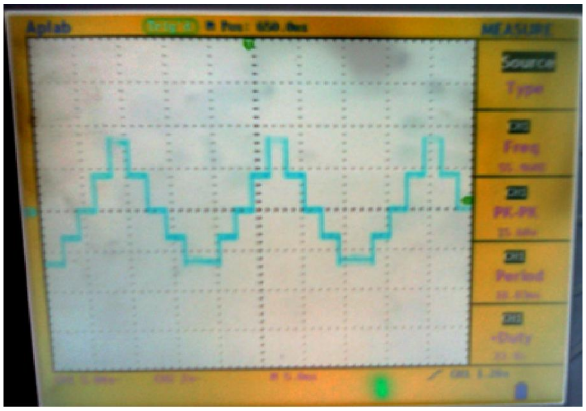
Current control Technique	THD %	Average switching frequency (kHz)
Adaptive Hysteresis band	4.52	5
Sine PWM	4.66	3.26
Fixed Hysteresis band	7.81	3.28

6. Experimental Results

To verify the performance of the proposed method, the proposed Adaptive Hysteresis Current Control method is applied to the five-level cascaded multilevel inverter. Figure 10 shows the experimental setup. The controller is implemented using an FPGA Xilinx Spartan-3E Atmel AT90USB2 USB controller; the Basys2 board provides the complete, ready-to-use hardware suitable for hosting circuits ranging from basic logic devices to complex controllers. Because of large collections of on-board input output devices and circuits are included countless designs can be created without the need for any other components like A/D & D/A conversion, motor drivers, sensor inputs etc. The use of FPGA allows very high speed control loops, resulting in significantly enhanced performance over microprocessor implementation [29]. The single phase H-bridge cascaded multilevel inverter has been designed and it mainly consists of 8 IRF 540N MOSFETs. The proposed controller has been tested on multilevel cascaded inverter without using PV arrays. The PV arrays are replaced by variable output DC power supply. The Figure 10 (b) shows the multilevel output voltage. This oscillographs demonstrates the good quality of the obtained voltage waveforms, confirming simulation results. Further, a smaller size filter may be used to convert the staircase multilevel output voltage to smoother sine wave.



(a)



(b)

Figure 10 (a) Experimental Setup, (b) Multilevel Inverter Output Voltage

7. Conclusion:

This paper presents a single-phase five-level cascaded multilevel inverter with adaptive hysteresis current control technique for solar PV applications. The PV array modeling, multilevel inverter circuit topology, control algorithm and operational principle and characteristics are analyzed in detail. From the result obtained, it is observed that the multilevel inverter and its adaptive hysteresis current controller results in constant switching frequency with less harmonic content. It is also suitable for PV applications. The results obtained with the proposed algorithm are compared with those obtained when using fixed hysteresis current controller and sine PWM controller in terms of THD and switching frequency. The results show that the THD of the five-level inverter with the proposed adaptive hysteresis band current controller is much lesser and provides constant switching frequency. The experimental result confirms and verifies the current control technique for the multilevel inverter in simulation.

Corresponding Author:
Mrs. K. Punitha
Department of EEE
Kalasalingam University
Anand Nagar, Krishnankoil,
Virudhunagar District 626 125, India
E-mail: kgpunitha@gmail.com

Appendix:

In this article, PV system comprising a boost-type DC-DC converter and a multilevel inverter is used to feed the power generated by the PV array to the grid and grid-connected loads. The conventional P & O method is used for MPPT and is explained in this appendix. One of the most successful and simplest methods for MPPT is P & O, in which the controller is to provoke perturbation by acting (decrease or increase) on the PWM duty cycle, observing the effect on the output PV power. 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, the operating point moves toward the MPP and, therefore, the operating voltage must be further perturbed in the same direction. Otherwise, if the power drawn from the PV array decreases, the operating point has moved away from the MPP and, therefore, the direction of the operating voltage perturbation must be reversed as shown in Figure 11.

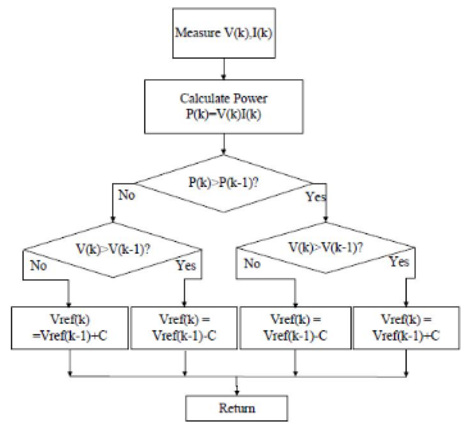


Figure 11. Flowchart of P & O MPPT Algorithm

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