Space Vector Control of Multi-Level Inverter for Grid Connected Photovoltaic System

P.Thirumurugan
Assistant Professor, Research Scholar, Department of Instrumentation and Control Engineering
Saranathan College of Engineering, Anna University,
Trichy, Tamilnadu, India,
thirum.tech16@gmail.com

S.Arockia Edwin Xavier
Assistant Professor, Department of Electrical and Electronics Engineering,
Thiagarajar College of Engineering
Madurai,India.
saexeee@gmail.com

Abstract— **This paper mainly depicts the total harmonic distortion rate (THD) of diode clamped multilevel inverter (DCMLI) for grid connected photovoltaic system. For this system, five and seven-level inverters have been considered. The photovoltaic system mainly consists of solar array which is controlled by fuzzy based Maximum Power Point Tracking (MPPT) technique. The Fuzzy logic control (FLC) based MPPT is then combined with the inverter so that the DC-DC converter is not necessary and finally the output will be accurate with fast response. DCMLI is controlled by space vector pulse width modulation technique (SVPWM). SVPWM is used because it provides low switching stress and low THD rate. Finally, the results obtained are verified and compared with existing methodology using MATLAB and Simulink environment and hardware setup.**

Keywords— ***DCMLI, Multi level inverter, fuzzy, MPPT, SVPWM, THD, MATLAB***

I. INTRODUCTION

Renewable energy sources derive their energy from existing flows of energy, such as sunshine, wind, flowing water, biological processes, and geothermal heat flows. A general definition of renewable energy sources is that renewable energy is captured from an energy resource that is replaced rapidly by a natural process such as power generated from the sun or from the wind. Currently, the most promising alternative energy sources include wind power, solar power, and hydroelectric power [1]. Other renewable sources include geothermal and ocean energies, as well as biomass and ethanol as renewable fuels. Every day, the sun delivers energy to the earth free of charge. We can use this free energy thanks to a technology called photovoltaic, which converts the sun's energy into electricity. Photovoltaic modules or panels are made of semiconductors that allow sunlight to be converted directly into electricity. These modules can provide a safe, reliable, maintenance-free and environmentally friendly source of power for a very long time. The amount of power generated by a PV generator depends on the operating voltage of the PV array. The PV system operates at its highest efficiency at the maximum power point. The maximum power operating point changes with insolation level and temperature. In order to increase the efficiency, MPPT controllers are used [2]-[3].MPPT is the technique used to track the maximum power from the PV array. Different tracking control strategies such as perturbation & observation, incremental conductance, parasitic capacitance, constant voltage, neural network and fuzzy logic control have been proposed to extract maximum power from the PV array. In this paper fuzzy control is used to track the maximum power from the PV array. Fuzzy Logic representations founded on fuzzy set theory try to capture the way humans represent and reason with real-world knowledge in the face of uncertainty [4]. Design of fuzzy is easy and implemented and the output is fast and accurate. The primary component in grid-connected PV systems is the inverter [5].

Multilevel voltage source inverter is recognized as an important alternative to the normal two-level voltage source inverter especially in high voltage applications. These new types of converters are suitable for high voltage and high power application due to their ability to synthesize waveforms with better harmonic spectrum [6]. A multilevel inverter not only achieves high power ratings, but also enables the use of renewable energy sources. The attractive features of the multilevel inverters are staircase waveform quality, common mode voltage, input current, switching frequency. Among the different topologies like diode clamped multilevel inverter, flying capacitor multilevel inverter and cascaded inverter with different DC sources, Neutral Point Clamped (NPC) or Diode clamped multilevel inverter topology is used in this paper. The generalized multilevel topology can balance each voltage level by itself regardless of load characteristics, active or reactive power conversion and without any assistance from other circuits at any number of levels automatically [7]. A fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most popular method of controlling the output voltage and this method is termed as Pulse-Width Modulation (PWM) Control. Abundant modulation techniques have been introduced for inverters like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse width Modulation (SVPWM), Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) [8]. Among all techniques Space Vector Pulse width Modulation (SVPWM) technique is used in this paper.

II. PHOTO VOLTAIC SYSTEM

Modern residential solar power systems use photovoltaic (PV) to collect the sun’s energy. Photo means produced by light, and voltaic is electricity produced by a chemical reaction. PV cells use solar energy to generate a chemical reaction that produces electricity. Each cell contains a semiconductor; most commonly silicon in one of several forms, with impurities diffused throughout, and is covered with a silk screen [9]. Cells are joined together by a circuit and frame into a module. Semiconductors allow the electrons freed from impurities by the sun’s rays to move rapidly and into the circuit, generating electricity. Using PV modules to generate electricity can significantly reduce pollution. The most energy used in creating solar panels is used to purify and crystallize the semiconductor material. The power delivered by a PV system of one or more photovoltaic cells is dependent on the irradiance, temperature, and the current drawn from the cells [10]-[11]. Figure 1 shows a simple model of a PV cell. R_S is the series resistance associated with connecting to the active portion of a cell or module consisting of a series of equivalent cells. Using Equation 1 and I-V measurements, the value of R_S can be calculated. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array.

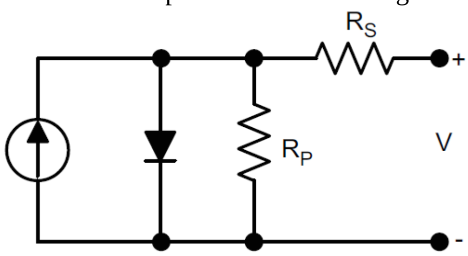

Fig.1. Simple PV cell

$$I = I_{Ph} - I_o \times \left(e^{\frac{q\times(v\times I\times R_s)}{n\times k\times T}} - 1\right) - \frac{v \times I \times R_s}{R_p} \quad (1)$$

where
I_{ph} = Photovoltaic current
I_O = Diode saturation current, T = Temperature (ºK)
q = Electron charge (1.6x10-19 C)
R_s = Series resistance
R_p = Parallel resistance
k = Boltzmann constant (1.38x10-23J/K)
n = Ideality factor

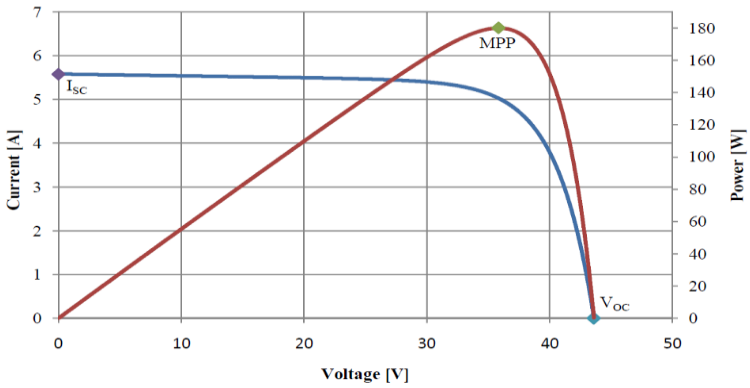

Fig.2. I-V and P-V characteristics of PV cell

In paper use PV array of KC200GT is used. KC200GT has following specifications: maximum power-200W; maximum power voltage-26.3V; maximum power current-7.61A.Working Principle of PV array: As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical effort. Transmitted light is absorbed within the semiconductor by using its energy to excite free electrons from a low energy status to an unoccupied higher energy level. When a solar cell is illuminated, excess electron-hole pairs are generated by light throughout the material, hence the p-n junction is electrically shorted and current will flow.The efficiency of PV array can be maximized by tracking the maximum power from the array. This tracking can be achieved by MPPT controller.

III. MULTI LEVEL INVERTER

Multilevel inverter is to synthesize a sinusoidal voltage from several levels of voltages. A multilevel power converter structure has been used in high power and medium voltage situations. The steps are increased to obtain an almost sinusoidal waveform. The number of switches involved is increased for every level increment. Fig.5 represents the circuit diagram for three phase six-level inverter. The switches are triggered by switching states [15]. Three phase six-level inverter has ten switches in each phase and each switch has parallel diode to avoid reverse conduction.

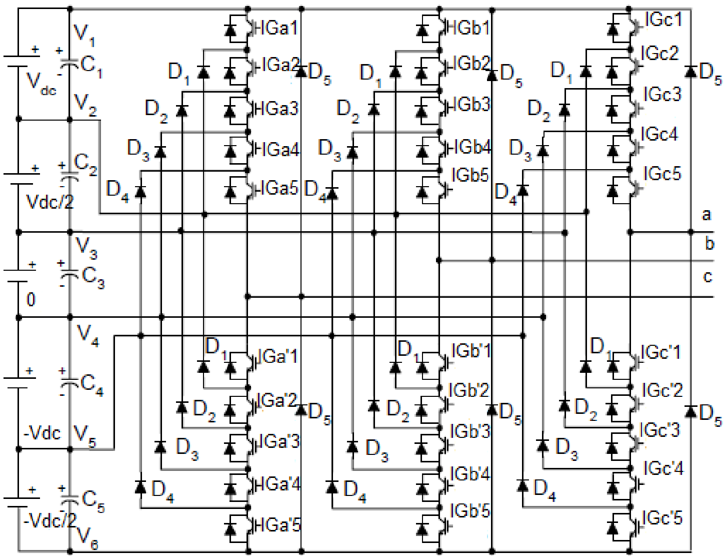

Fig.5 Circuit diagram of three phase six-level inverter

Three phase six level inverter has ten switches in each leg and each switch has parallel diode to avoid reverse conduction. Each leg has five complementary pairs that is turning ON one of the switches of the pair require that the other switch of that pair to be OFF. The complementary pair of phase is (IGa1, IGa'1), (IGa2, IGa'2), (IGa3, IGa'3), (IGa4, IGa'4), (IGa5, IGa'5). For a six-level inverter, a set of five switches is on at any given time. Generally, switches are denoted by IGx1.IG indicates the switch IGBT, x denotes the phase of the inverter and the last numeric term denotes the position of the switch in the x phase.

IV SPACE VECTOR PULSE WIDTH MODULATION

To control multilevel converters, Space Vector Pulse Width Modulation (SVPWM) one of the PWM strategies is most effective, which has equally divided zero voltage vectors describing a lower total harmonic distortion (THD) [16]. Although the complexity presents in SVPWM strategy (many output vectors) compared with the carrier-based PWM, it remains the preferred one, because it reduces the power losses by minimizing the power electronic devices switching frequency [17]. The space-vector pulse width modulation (SVPWM) strategy reduces the switching losses by limiting the switching to the two thirds of the pulse duty cycle [18]. SVPWM generates higher voltages with low total harmonic distortion and works very well with field oriented (vector control) schemes for motor control. High quality output spectra can be obtained by eliminating several low order harmonics by adopting a suitable harmonic elimination technique.

In this modulation technique the three phase quantities can be transformed to their equivalent 2-phase quantity either in synchronously rotating frame or stationary frame. From this 2-phase component the reference vector magnitude can be found and used for modulating the inverter output [19]. Switching vectors and sectors of SVPWM are shown in fig.6.

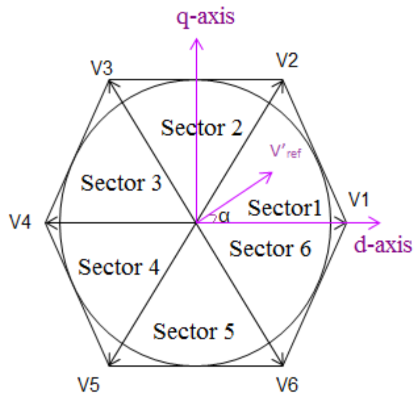

Fig.6 Basic switching vectors and sectors

The vectors (V1 to V6) divide the plane into six sectors (each sector: 60 degrees). V'_{ref} is generated by two adjacent non-zero vectors and two zero vectors. A three-phase voltage vector is transformed into a vector in the stationary d-q coordinate frame which represents the spatial vector sum of the three-phase voltage. This is coordinate transformation (abc reference frame to the stationary d-q frame).

For the inverter circuit shown in fig.5 the line to line voltage $[V_{ab}, V_{bc}, V_{ca}]^T$ when using SVPWM is determined by following [20]

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2}$$

The line to neutral voltage $[V_{an}, V_{bn}, V_{cn}]^T$ for the inverter circuit shown in fig.5 is obtained by

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3}$$

To realize space vector some values are to be calculated. i.e. V_d, V_q, V'_{ref}, firing angle (α), time duration and switching time of each switch. To find V_d, V_q, V'_{ref} and firing angle (α) consider the coordinate transformation shown in fig.7.

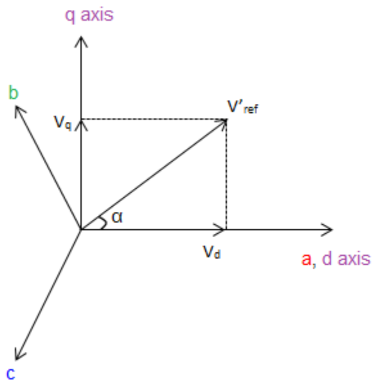

Fig.7 Coordinate transformation

From fig.7,

For direct axis,

$$V_d = V_{an} - V_{bn}\ .\cos 60 - V_{cn}\ .\cos 60$$

$$V_d = V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn} \quad (4)$$

For quadrature axis,

$$V_q = 0 + V_{bn}\ .\cos 30 - V_{cn}\ .\cos 30$$

$$V_q = 0 + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn} \quad (5)$$

From 4 and 5 we have,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (6)$$

For reference,

$$|V'_{ref}| = \sqrt{V_d{}^2 + V_q{}^2} \quad (7)$$

Firing angle is given by,

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) \quad (8)$$

Determination of time duration (T_1, T_2, T_0):

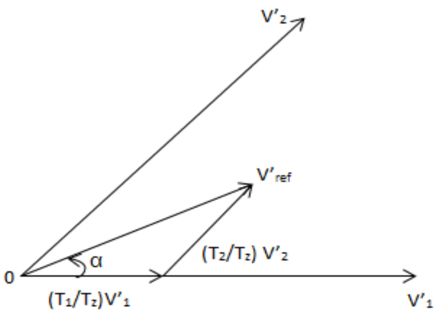

Fig.8 Time duration

$$T_1 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}\,T_z|V'_{ref}|}{V_{dc}}\left(\sin\frac{n}{3}\pi - \alpha\right)$$

$$T_1 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(\sin\frac{n}{3}\pi\cos\alpha - \cos\frac{n}{3}\pi\sin\alpha\right) \quad (9)$$

$$T_2 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right)$$

$$T_2 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(-\cos\alpha\sin\frac{n-1}{3}\pi + \sin\alpha\cos\frac{n-1}{3}\pi\right) \quad (10)$$

$$T_0 = T_z - T_1 - T_2 \quad (11)$$

Where, n= 1 to 6 (that is sectors 1 to 6);

$$0 \le \alpha \le 60^0; \; T_z = \frac{1}{f_z}.$$

By using the above formulas we calculate the time instants, firing angle (α), reference voltage and sectors voltage. By calculating these values we simulate the model and corresponding outputs are obtained.

Figure 9 shows the space vector diagram for three level Diode Clamped systems, where each digit of the space vector identifier represents the voltage level to which the A, B and C phase legs are respectively switched. The difficult task is selecting the optimum set of space vectors for a given reference phasor. Once the optimum switching space vector sequence for continuous modulation has been identified, it must be placed in each switching period to optimize the harmonic profile of the waveform.

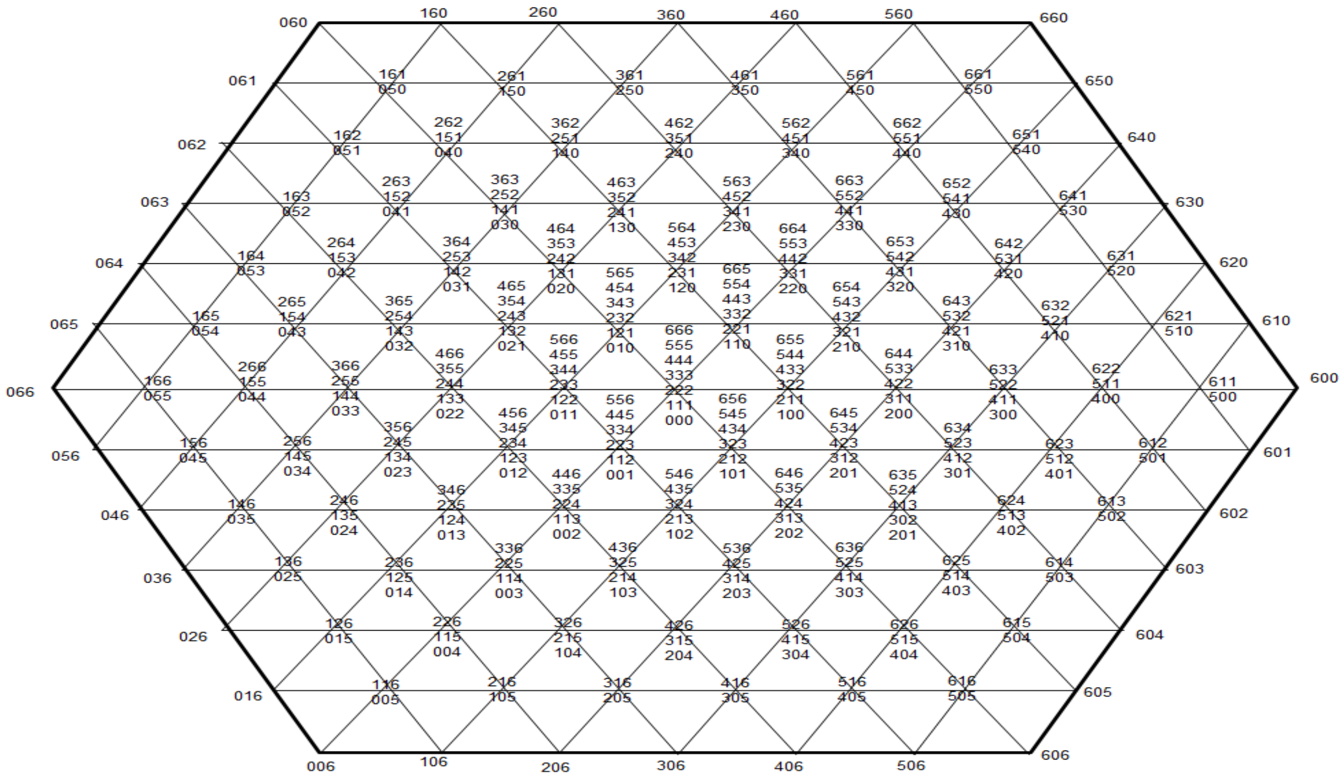

Fig.9 Switching instant of three phase seven level inverter for SPVWM

V HARDWARE AND SIMULATION RESULT

This paper analyses the harmonic rate of three phase five and seven level inverter in terms of THD rate. Simulation results are analysed and compared between the levels of the multilevel inverter for SVPWM technique. Switches in the inverter are triggered by using pulse width modulation techniques like Space vector pulse width modulation. The shape of the output voltage of the inverter is determined by the modulating index. In this section three phase five-level, and seven-level inverter are considered.

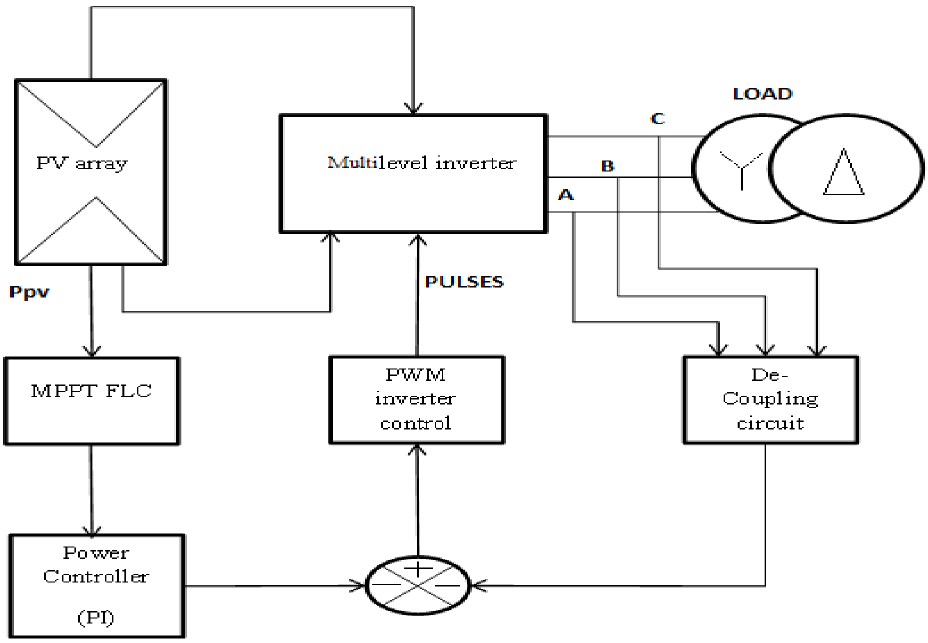

Fig.10 Block diagram for inverter circuit

Fuzzy Logic Control (FLC) is considered to control the PV array and to obtain the maximum power point. FLC tracks the maximum point accurately and easily in all conditions. Since PV array has a nonlinear characteristics FLC works good compared to other tracking techniques. FLC rules are framed in table.1.

Hardware setup

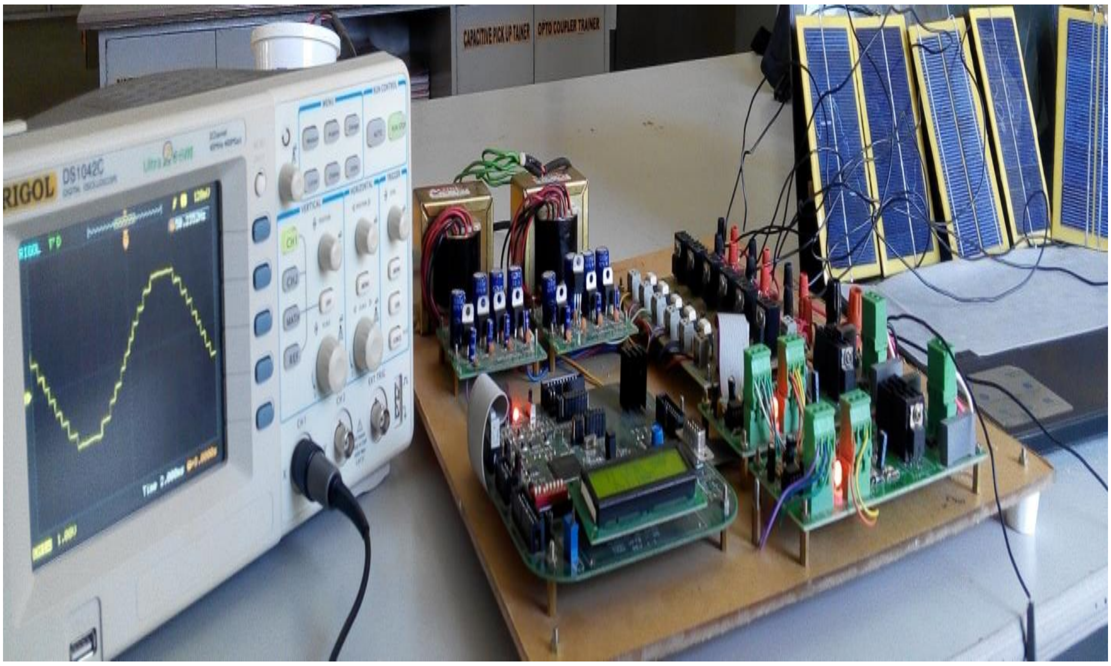

Fig.11 Experimental setup

Space vector waveform and their gating signals are shown in fig.12 and fig.13. Space vector waveform is different from sine waveform in their structure.

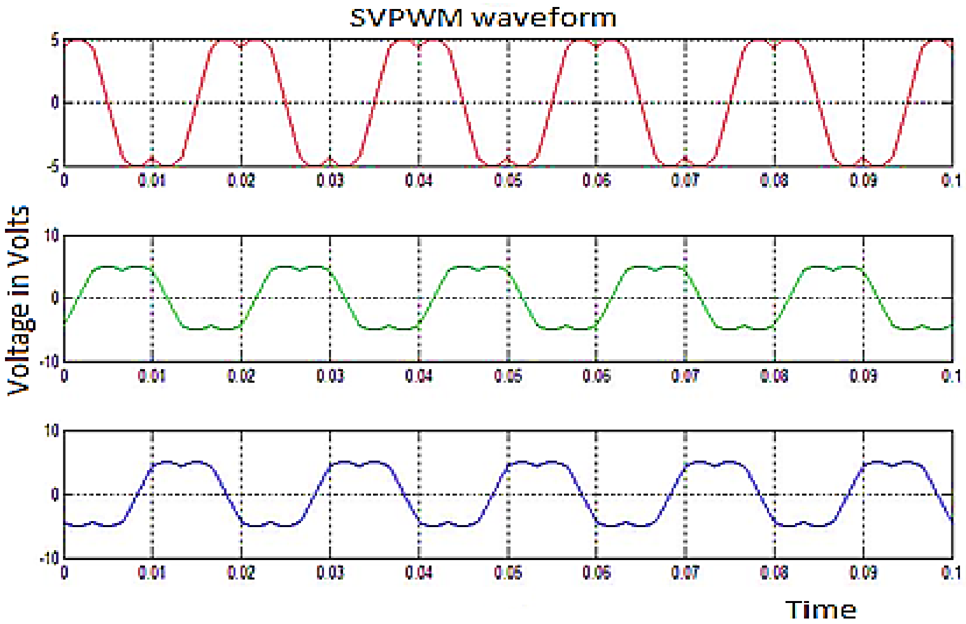

Fig.12 Space Vector Waveform

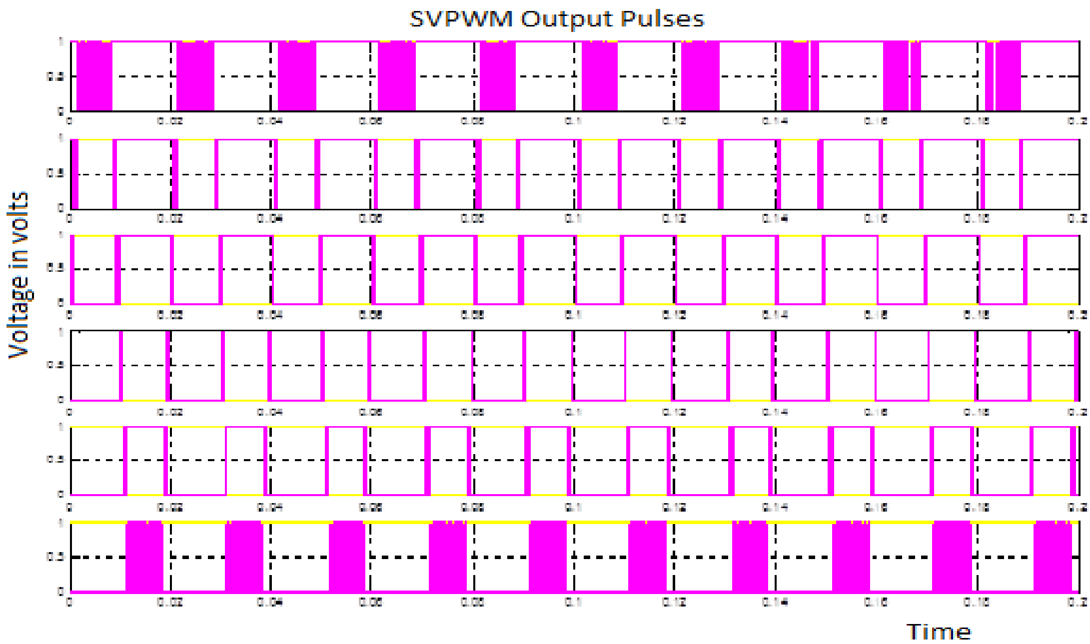

Fig.13 SVPWM gate Pulses

The table of comparison for harmonic rate is shown in table.1. The table compares the THD rate for three phase five-level and seven-level inverter for open loop and closed loop SVPWM technique.

TABLE.1
COMPARISON TABLE

Sl.No	No.of levels	THD (%) for open loop	THD (%) for closed loop
1	5	16.32	14.28
2	7	14.86	11.94

From the comparison table harmonic rate is low for high level inverter. The corresponding THD graphs are shown below. First consider the THD rate of five-level inverter for both open and closed loop system.

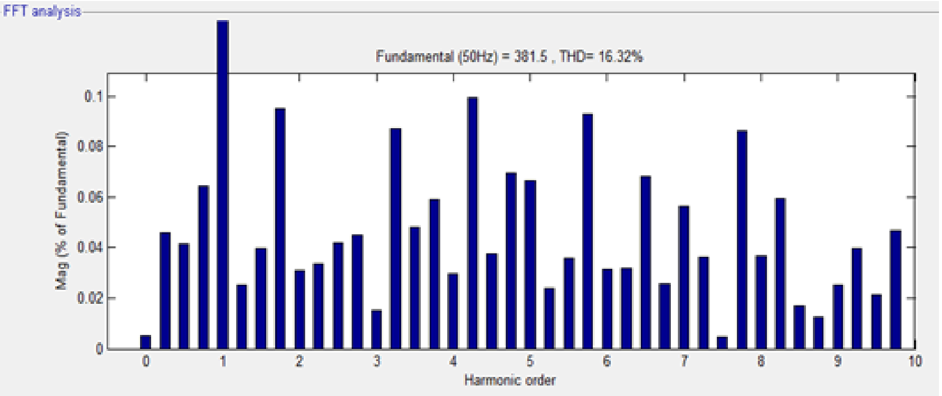

Fig.14 Total Harmonic Reduction of three phase five level inverter for open loop of SVPWM.

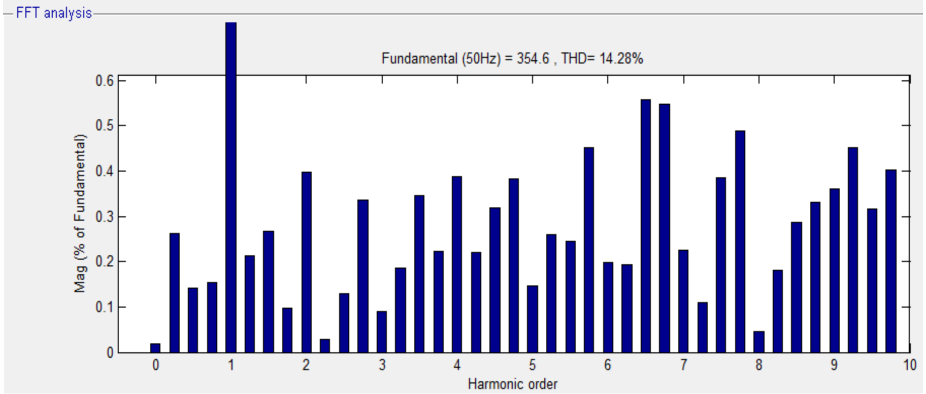

Fig.15 Total Harmonic Reduction of three phase five level inverter for closed loop of SVPWM.

The THD rate of three phase five-level inverter for both open loop and closed loop are shown in fig.14 and 15 respectively. From the figures THD rate is about 16.32% and 14.28%. Here closed loop system has low THD rate compared to open loop system.

Now, consider the THD of three phase seven-level inverter for both open loop and closed loop system.

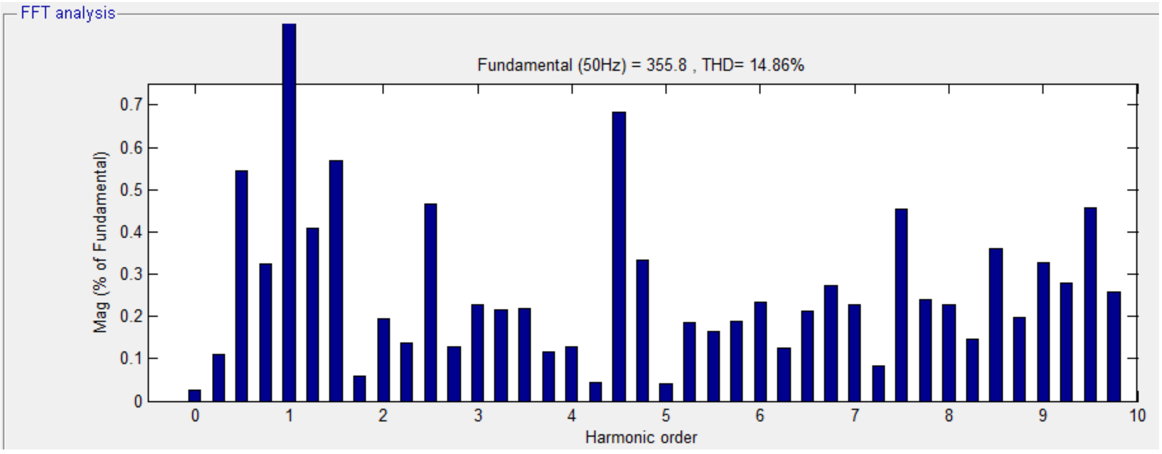

Fig.16 Total Harmonic Reduction of three phase seven level inverter for open loop of SVPWM.

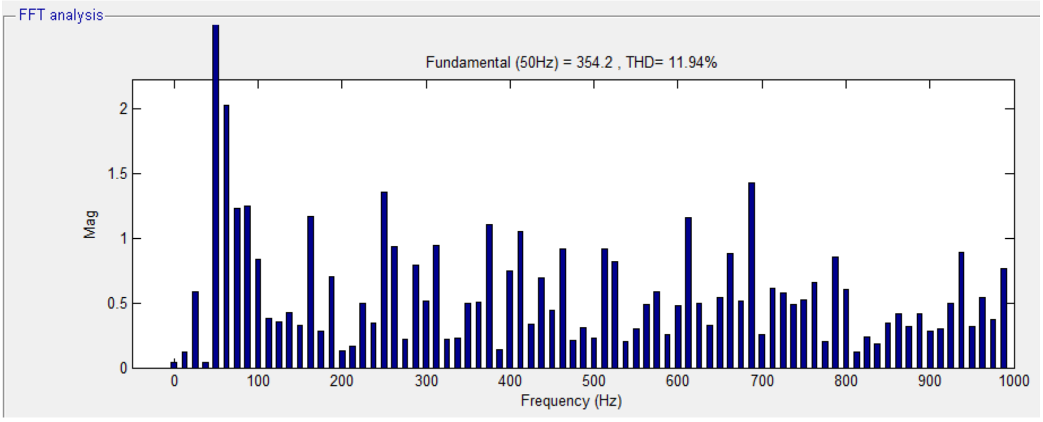

Fig.17 Total Harmonic Reduction of three phase seven level inverter for closed loop of SVPWM.

The THD rate of three phase seven-level inverter for both open loop and closed loop are shown in fig.16 and 17 respectively. From the figs THD rate is about 14.86% and 11.94%. Here closed loop system has low THD rate compared to open loop system.

VI CONCLUSION

Based on simulation and experimental results, it is evident that the reduction of THD rate by using high multilevel inverter. Diode clamped inverter topology thereby provides less stress, low harmonics when compared to other topologies. The simulation of three phase five level and seven- level inverter for SVPWM technique is thus designed and compared in terms of harmonic distortion rate. However, the most significant advantages of SVPWM are fast dynamic response and wide linear range of fundamental voltage when compared with the conventional PWM. Therefore FFT analysis shows the THD rate for both open loop and closed loop. Thus, it has been concluded that the THD rate is low high level inverter. FLC MPPT works simply well when compared to other tracking techniques and it avoids the DC-DC chopper. In order to get low THD rate, multilevel inverter can be expanded by increasing the number of levels. Thus based on experimental results, High quality sinusoidal output response (AC voltage) is achieved without any distortion.

IV. References

[1] P.Thirumurugan, R.Preethi, Closed Loop Control of Multilevel Inverter Using SVPWM for Grid Connected Photovoltaic System, International journal of Advanced Research in Electrical , Electronics and Instrumentation Engineering, Vol.2, No. 4, April 2013, pp.1561-1572.
[2] P.Thirumurugan, R.Preethi, B.Sangeetha, Comparison of Closed Loop Control for Three level and Five level Inverter for Photovoltaic System, IEEE 2nd International Conference on Communication and Signal Processing, 2013, pp.603-607.
[3] A.Ravi, P.S.Manoharan, J.Vijay Anand, Modeling and Simulation of Three Phase Multilevel Inverter for Grid Connected photovoltaic System, ELSEVIER, 2011.
[4] Sofia.Lalouni, Djamila.Rekioua, Modeling and Simulation of a Photovoltaic System Using Fuzzy Logic Controller, Second International Conference on Developments in eSystems Engineering, 2009, pp.23-28.
[5] F.Bouchafaa, D.Beriber, M.S.Boucherit, Modeling and Control of a Grid Connected PV Generation System, 18th Mediterranean Conference on Control & Automation, June 23-25 2010, pp.315-320.
[6] Murugesan.G, Jagabar Sathik.M, Praveen.M, A New Multilevel Inverter Topology Using Less Number of Switches, International Journal of Engineering Science and Technology (IJEST), Vol.3, No.2, Feb 2011, pp.1500-1510.
[7] Fang Zheng Peng, Senior Member, IEEE, A Generalised Multilevel Inverter Topology with Self Voltage Balancing, IEEE Transactions on Industry Applications, VOL. 37, NO. 2, MARCH/APRIL 2001, pp.611-618.
[8] P.Thirumurugan, P.S.Manoharan, M.Valanrajkumar, VLSI Based Inverter Switching Control, International Conference on Mathematical Modeling and Applied Soft Computing, Vol.2, July.2012, pp.965-973.
[9] Soeren Baekhoej Kjaer, John K.Pedersen, and Frede Blaabjerg, A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules, IEEE Transactions on Industry Applications, Vol.41, No.5, September/October 2005, pp.1292-1306.
[10] Joe-Air Jiang, Tsong-Liang Huang, Ying-Tung Hsiao, Chia-Hong Chen, Maximum Power Tracking for Photovoltaic Systems, Tamkang Journal of Science and Engineering, Vol.8, No.2, 2005, pp.147-153.
[11] I. H. Altas, A.M. Sharaf, A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment, IEEE 2007, pp.341-345.
[12] Subiyanto, Azh Mohamed, and MA HAnnan, Hardware Implementation of Fuzzy Logic Based Maximum Power Point Tracking Controller for PV Systems, 4th International Power Engineering and Optimization Conf. (PEOCO2010), 23-24 June 2010, pp.435-439.
[13] Rohin.M.Hilloowala, Adel.M.Sharaf, A Rule-Based Fuzzy Logic Controller for a PWM Inverter in Photo-voltaic Energy Conversion Scheme, IEEE, pp.762-769.
[14] Pongsakor Takun, Somyot Kaitwanidvilai, Chaiyan Jettanasen, Maximum Power Point Tracking Using Fuzzy Logic Control for Photovoltaic System, Proceedings of the International MultiConference of Engineers and Computer Scientists 2011 Vol.II, IMECS, March 16-18, pp.986-990.
[15] M.Kaliamoorthy and R.M.Sekar, J.Gerald Christopher Raj, A New Single-Phase PV fed Five-Level Inverter Topology Connected to the Grid, IEEE 2010, pp.196-203.

[16] Pankaj H Zope, Pravin G.Bhangale, Prashant Sonare, S. R.Suralkar, Design and Implementation of Carrier based Sinusoidal PWM Inverter, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol.1, Issue.4, October 2012, pp.230-236.

[17] D.Dujic, E.Levi, M.Jones, G.Grandi, G.Serra, A.Tani, Continuous PWM Techniques for Sinusoidal Voltage Generation with Seven-Phase Voltage Source Inverters, IEEE 2007, pp.47-52.

[18] K. Vinoth Kumar, Prawin Angel Michael, Joseph P. John, Dr. S. Suresh Kumar, Simulation and Comparison of SPWM and SVPWM Control for Three Phase Inverter, ARPN Journal of Engineering and Applied Sciences, Vol.5, No.7, July 2010, pp.61-74.

[19] P.Upendra Kumar, Prashant Kumar Das, K. Durga Malleswara Rao, B.Venkata Ramana, Modelling And Analysis Of Multi Level Inverters Using Space Vector Pulse Width Modulation (SVPWM), International Journal of Engineering Research and Applications (IJERA), Vol. 2, Issue 2, Mar-Apr 2012, pp.536-542.

[20] H.W. van der Broeck, H.-C. Skudelny, G.V. Stanke, Analysis and Realization of a Pulse Width Modulator based on voltage space vectors, IEEE Transactions on Industry Applications, vol.24, 1988, pp.142-150.