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Closed Loop Control of Multilevel Inverter Using SVPWM for Grid Connected Photovoltaic System

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ABSTRACT: This paper discuss about the closed loop control of Diode Clamped Multilevel Inverter (DCMLI) for grid connected photovoltaic (PV) system. PV array is controlled and maximum power is obtained by fuzzy based MPPT algorithm. DC-DC converter is not needed because fuzzy MPPT is integrated with the inverter so that the output shows accurate and fast response.Space Vector Pulse Width Modulation (SVPWM) is used to control the inverter because of its highest efficiency and simulation is achieved through MATLAB/Simulink. The simulation results of three phase three-level and five-level diode clamped multilevel inverter are compared in terms of Total Harmonic Distortion (THD) rate.

Keywords: DCMLI, PV system, fuzzy, SVPWM, THD.

I. INTRODUCTION

The need for renewable energy sources is on the rise, because of the acute energy crisis in the world today. Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat [1], [2]. Here, solar power is used as a source to multilevel inverter.

The two principal classifications of photovoltaic system are grid-connected or utility-interactive systems and stand-alone systems. With the appropriate power conversion equipment, PV systems can produce alternating current (AC) compatible with any conventional appliances, and can operate in parallel with, and interconnected to, the utility grid. The PV system operates at its highest efficiency at the maximum power point. The maximum power operating point changes with insolation level and temperature [3].

In order to increase the efficiency, MPPT controllers are used. 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 [4]. 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. 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]. PV generation has numerous advantages like emitting noise, fuel costs, maintenance and it does not cause pollution.

Multilevel inverters are suitable for high voltage and high power applications 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. Using multilevel technique, the amplitude of the voltage is increased, stress in the switching devices is reduced and the overall harmonics profile is improved. 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.

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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 like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) [7]. Among all techniques Space Vector Pulse Width Modulation (SVPWM) technique is used in this paper.

II. **PV SYSTEM**

PV arrays are built up with combined series/parallel combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model shown in fig.1.

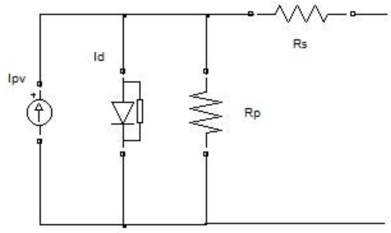

Fig.1 Equivalent circuit model of solar cell

The PV cell output voltage is a function of the photocurrent that mainly determined by load current depending on the solar irradiation level during the operation [8].

$$V_c = \frac{AkT_c}{e}\ln\left(\frac{I_{ph}+I_o-I_c}{I_o}\right) - R_s I_c \qquad (1)$$

where the symbols are defined as follows:

V_c: cell output voltage, V.
e: electron charge (1.602 × 10-19 C).
k: Boltzmann constant (1.38 × 10-23 J/^{0}K).
I_c: cell output current, A.
I_{ph}: photocurrent, function of irradiation level and junctiontemperature (5 A).
I_0: reverse saturation current of diode (0.0002 A).
R_s: series resistance of cell (0.001 Ω).
T_c: reference cell operating temperature (20 °C).

The curve fitting factor A is used to adjust the I-V characteristics of the cell obtained from (1) to the actual characteristics obtained by testing equation (1) gives the voltage of a single solar cell which is then multiplied by the number of the cells connected in series to calculate the full array voltage. The electrical system powered by solar arrays requires special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell. Thus the change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants, C_{SV} and C_{SI}, which are the correction factors for changes in cell output voltage V_C and photocurrent I_{ph}, respectively [9]:

$$C_{sv} = 1 + \beta_T \alpha_S (S_x - S_C) \qquad (2)$$

$$C_{SI} = 1 + \frac{1}{S_C}(S_x - S_C) \qquad (3)$$

where S_C is the benchmark reference solar irradiation level during the cell testing to obtain the modified cell model. S_x is the new level of the solar irradiation. β_T, γ_T values are varied according to the photovoltaic cell used.

The constant $\alpha_{S,}$ represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level. Using correction factors C_{SV} and C_{SI}, the new values of the cell output voltage V_{CX} and photocurrent I_{phx} are obtained for the new temperature T_x and solar irradiation S_x as follows:

$$V_{CX} = C_{TV} C_{SV} V_C \tag{4}$$

$$I_{phx} = C_{TI} C_{SI} I_{ph} \tag{5}$$

where

$$C_{TV} = 1 + \beta_T (T_a - T_x) \tag{6}$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_C} (T_x - T_a) \tag{7}$$

V_C and I_{ph} are the benchmark reference cell output voltage and reference cell photocurrent, respectively.

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. **FUZZY BASED MPPT**

MPPT is a technique used to track the maximum power from the solar panel. Quick tracking under changing conditions, small output power fluctuation, simplicity and low cost are the general requirements for an MPPT. MPPT algorithms are necessary because solar arrays have nonlinear voltage-current characteristics with a unique point where the power produced is maximum [10]. One of the computational methods which have demonstrated fine performance under different environmental operating conditions is the fuzzy based maximum power point tracking technique.

The fuzzy control has the advantage to be robust and relatively simple to design, since it does not require the knowledge of the exact model. A Mamdani fuzzy logic controller has been proposed to perform the MPPT, this kind of controller are usually used in feedback control mode, because they are computationally simple, present low sensibility to noise in the input (what is important in power system), and can easily represent the knowledge about the control action.

Basically FLC has three parts namely: Fuzzification, Inference Engine and Defuzzification.

A. Fuzzification

The fuzzification is the process of converting the crisp set into linguistic fuzzy sets using fuzzy membership function. The concept of linguistic variable was introduced to process the natural language. The membership function is a curvature that describes each point of membership value in the input space [11]. Variables are assigned as Negative Big $(-ve\ B)$, Negative Medium $(-ve\ M)$, Negative Small $(-ve\ S)$, Zero, Positive Small$(+ve\ S)$, Positive Medium $(+ve\ M)$, and Positive Big $(+ve\ B)$.

The inputs of fuzzification are the error and change in error. The value of input error E (k) and change in error CE (k) are normalized by an input scaling factor. The input scaling factor has been designed such that input values are between -0.032 and 0.032. Membership function has many structures; among those triangular memberships function is used shown in fig.2 because for any particular input there is only one dominant fuzzy subset.

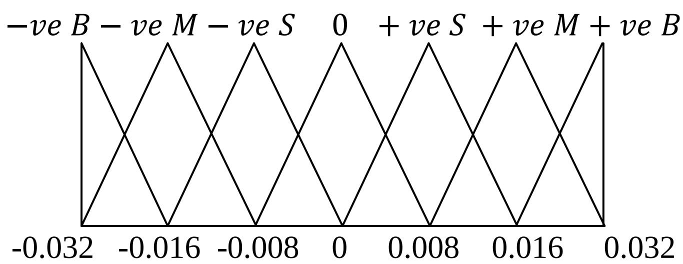

Fig.2 Triangular membership function

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Fuzzy rule base is the basic function of fuzzification. A collection of rules referring to a particular system is known as fuzzy rule base. Fuzzy rule base for these seven linguistic variables is shown in table.1

TABLE 1
FUZZY RULE BASE

E(k)	CE(k)						
	−veB	−veM	−veS	Zero	+veS	+veM	+veB
−veB	−veB	−veB	−veB	−veB	−veM	−veS	zero
−veM	−veB	−veB	−veB	−veM	−veS	zero	+veS
−veS	−veB	−veB	−veM	−veS	zero	+veS	+veM
zero	−veB	−veM	−veS	zero	+veS	+veM	+veB
+veS	−veM	−veS	zero	+veS	+veM	+veB	+veB
+veM	−veS	zero	+ves	+veM	+veB	+veB	+veB
+veB	zero	+veS	+veM	+veB	+veB	+veB	+veB

B. Inference Engine

Fuzzy inference engine is an operating method that formulates a logical decision based on the fuzzy rule setting and transforms the fuzzy rule base into fuzzy linguistic output [12]. Fuzzy linguistic descriptions are formal representations of systems made through fuzzy IF-THEN rules. They encode knowledge about a system in statements of the form: IF (a set of conditions) are satisfied THEN (a set of consequents) can be inferred. There are several methods for this such as Max-Min method, Max-Dot method. Inference engine is otherwise called as decision-making logic.

C. Defuzzification

The last step in the FLC process is the defuzzification. These will have a number of rules that transform a number of variables into a fuzzy result, that is, the result is described in terms of membership in fuzzy sets. Several methods are available for defuzzification such as centroid method, centre of sums, and mean of maxima. The Centre of Gravity (COG) defuzzification method is used [13]. Centre of gravity method is otherwise called as Centroid method, Centre of area method.

IV. MULTILEVEL INVERTER

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 [14]. Fig.3 represents the circuit diagram for three phase five-level inverter. The switches are triggered by switching states [15].Three phase five-level inverter has eight switches in each phase and each switch has parallel diode to avoid reverse conduction.

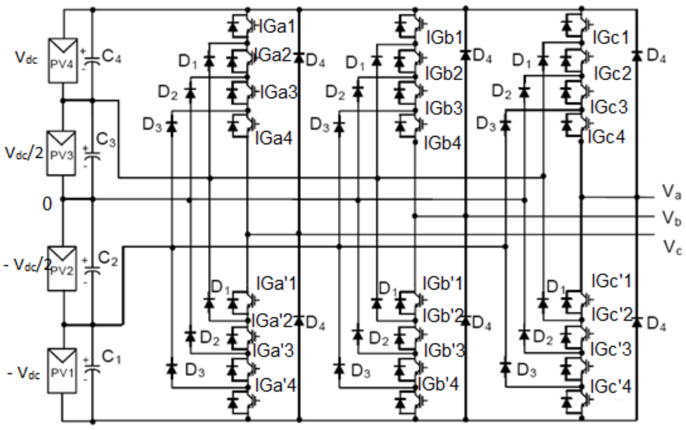

Fig.3 General structure of three phase five level inverter

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Each phase has four complementary pairs that is, turning on one of the switches of the pair, require that the other switch of that pair to be off [16]. The complementary pair of phase a is (IGa1, IGa'1), (IGa2, IGa'2), (IGa3, IGa'3), (IGa4, IGa'4). Here 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. The switching table for the circuit shown in fig.3 is indicated in table.2. Switch condition 0 means OFF state and 1 indicates ON state. In general for an m-level inverter m-1 switches should be ON at any given time. The m-level NPC inverter has an m-level output phase voltage and a 2(m-1) level output line voltage. The number of diodes required for each phase would be 2(m-2).

TABLE2
SWITCHING STATES OF THREE PHASE FIVE LEVEL INVERTER FOR PHASE a

Switching states	IGa1	IGa2	IGa3	IGa4	IGa'1	IGa'2	IGa'3	IGa'4
$+V_{dc}$	1	1	1	1	0	0	0	0
$+V_{dc}/2$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc}/2$	0	0	0	1	1	1	1	0
$-V_{dc}$	0	0	0	0	1	1	1	1

An m-level NPC inverter has m-1 capacitors on the DC bus. These capacitors are used as a filter circuit. Capacitor voltage is Vdc and from table 2 it is understood that a set of four switches is ON at any given time. The clamping diodes are used to block the reverse voltage. For example if the negative sides of phase a are ON means, the D1 diode block $-Vdc/2$, D3 diode blocks$+Vdc/2$.

V. 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) is used [17],[18]. 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 [19].

SVPWM generates higher voltages with low total harmonic distortion and works very well with field oriented (vector control) schemes for motor control. 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.
Basic switching vectors and sectors of SVPWM are shown in fig.4.

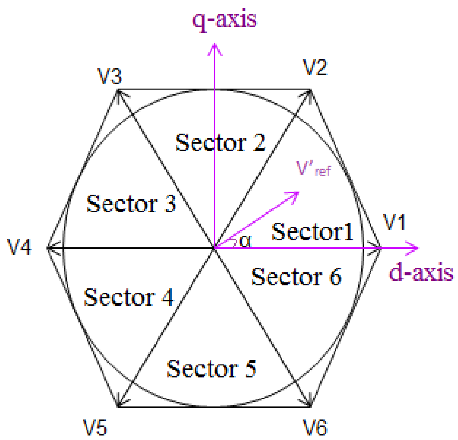

Fig.4 Basic switching vectors and sectors

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

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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 five-level inverter shown in fig.3 the line to line voltage $[V_{ab}, V_{bc}, V_{ca}]^T$ when using SVPWM is determined by following [20]

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (6)$$

The line to neutral voltage $[V_{an}, V_{bn}, V_{cn}]^T$ for the inverter circuit shown in fig.3 is obtained by

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (7)$$

To realize space vector some values are to be calculated. i.e. V_d, V_q, V'_{ref}, firing angle 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.5.

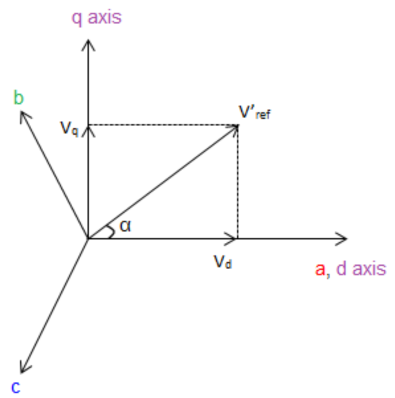

Fig.5 Coordinate transformation

From fig.5,

For direct axis,

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

$$V_d = V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn} \quad (8)$$

For quadrature axis,

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

$$V_q = 0 + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn} \quad (9)$$

From 8 and 9 we have,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (10)$$

For reference,

$$|V'_{ref}| = \sqrt{V_d^{\,2} + V_q^{\,2}} \quad (11)$$

Firing angle is given by,

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) \quad (12)$$

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

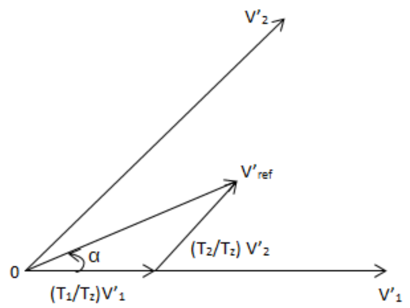

Fig.6 Time duration

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

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

$$T_1 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(\sin\frac{n}{3}\pi\cos\alpha - \cos\frac{n}{3}\pi\sin\alpha\right) \quad (13)$$

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

$$T_2 = \frac{\sqrt{3}T_z|V'_{ref}|}{V_{dc}}\left(-\cos\alpha\sin\frac{n-1}{3}\pi + \sin\alpha\cos\frac{n-1}{3}\pi\right) \quad (14)$$

$$T_0 = T_z - T_1 - T_2 \quad (15)$$

Where, n= 1 to 6 (that is sectors 1 to 6); 0≤α≤60^0; $T_z = \frac{1}{f_s}$.

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 7 shows the space vector diagram for five 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.

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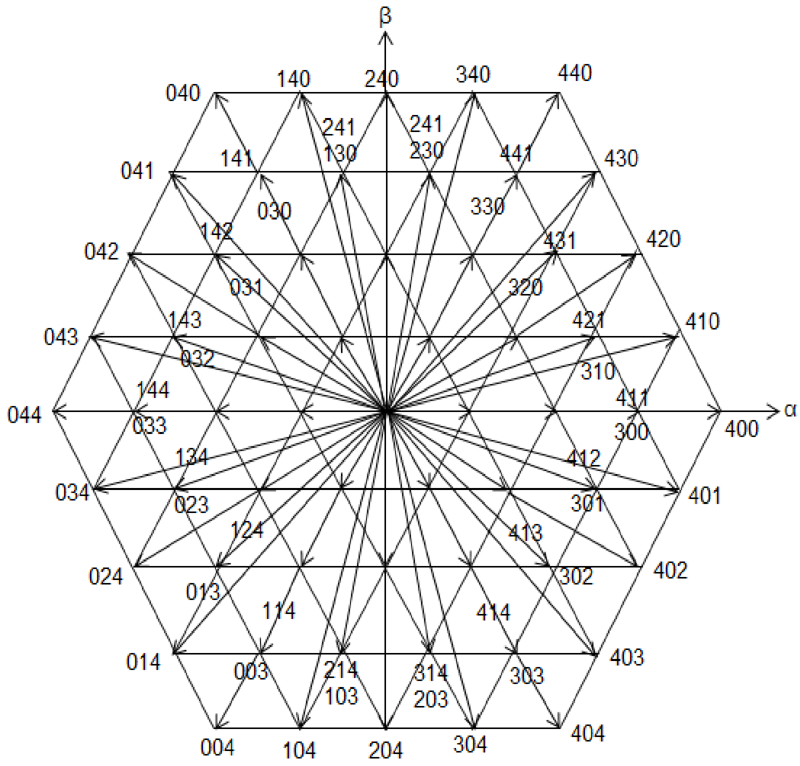

Fig.7 Space vector states for five level inverter

Switching table for five-level inverter is listed in table 2. The output voltage space vector is identified by combination of switching states $V_{dc}, {}^{V_{dc}}/_{2}, -V_{dc}, {}^{-V_{dc}}/_{2}$ of the three legs.

VI. MATLAB SIMULATION RESULTS

This paper analyses the harmonic reduction of three phase multilevel inverter in terms of THD rate for the inverter circuit shown in fig.8. Simulation results are analysed and compared between the levels of the multilevel inverter for SVPWM technique. Switches in the inverter are triggered by using space vector pulse width modulation technique. The shape of the output voltage of the inverter is determined by the modulating index.

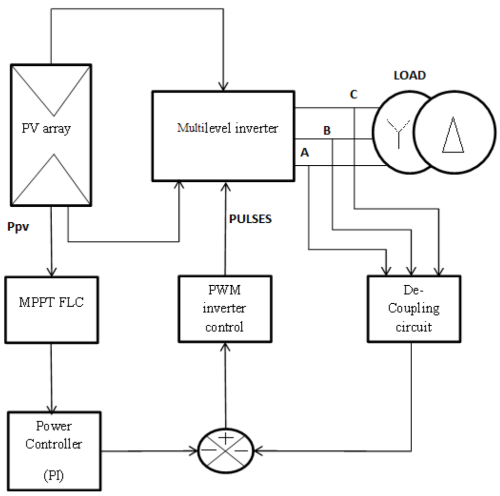

Fig.8 Block diagram for inverter circuit

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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. Space vector waveform and their gating signals are shown in fig.9 and fig.10 respectively. Space vector waveform is different from sine waveform in their structure.

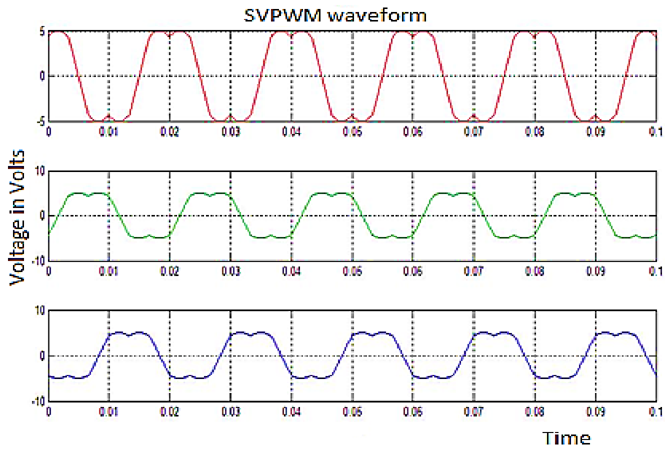

Fig.9 Space Vector Waveform

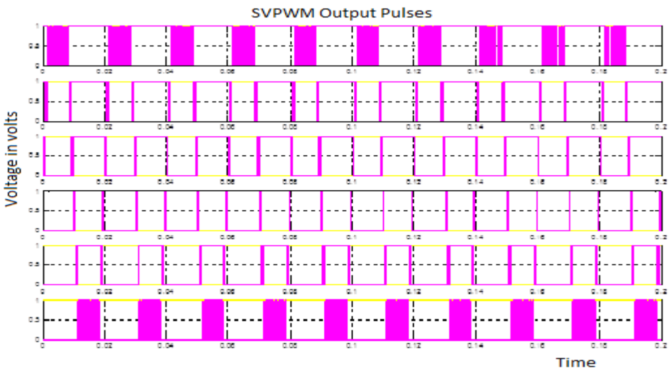

Fig.10 SVPWM gate Pulses

The output voltage for three phase five level has five levels which is shown in fig.11. The levels of the output voltage vary according to the level of the multilevel inverter.

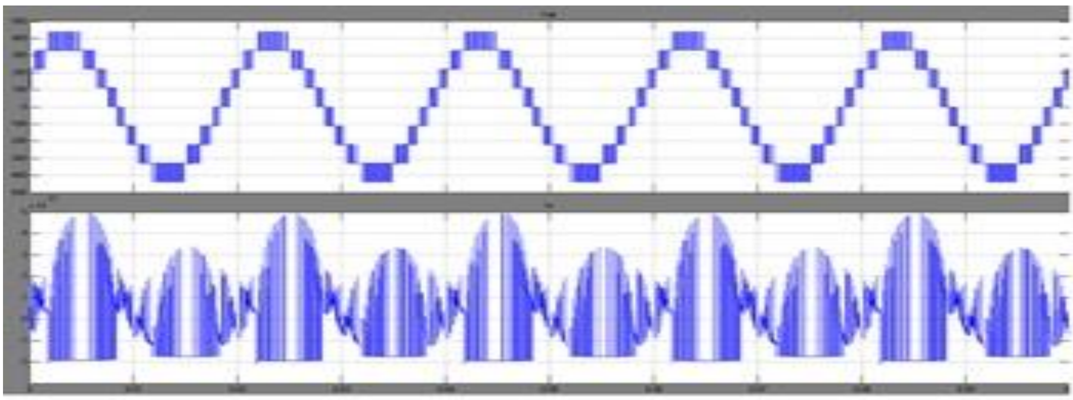

Fig.11 voltage and current waveforms for three phase five level inverter

The voltage waveform denotes the line voltage of five-level inverter between phases a and b. The supply voltage is 400V. The current waveform denotes the phase a current. The table of comparison is shown in table.3.

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TABLE 3
THD COMPARISON

SL.NO	NO.OF LEVELS	THD% (OPEN LOOP)	THD% (CLOSED LOOP)
1	3	32.14	30.98
2	5	16.32	12.36

THD rate is low for five-level inverter when compared to three-level inverter. SVPWM technique is chosen because of its high efficiency, low switching stress.

For three-level inverter the THD rate is about 32.14% for open loop SVPWM inverter, and it is about 30.98% for closed loop SVPWM inverter shown in figures 12 and 13 respectively.

For five-level inverter harmonic rate is 16.32% and 12.36% for open loop and closed loop SVPWM inverter which is described in figures 14 and 15. These harmonic distortion rates are less for SVPWM inverter when compared to SPWM (Sinusoidal Pulse Width Modulation).

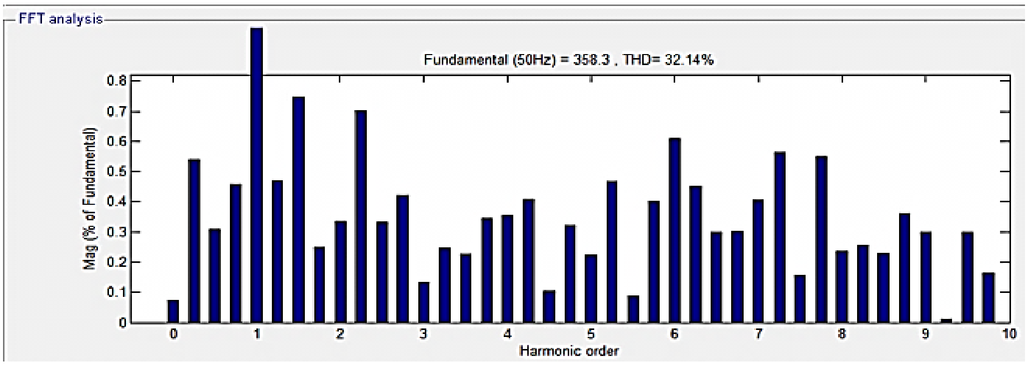

Fig.12 Total Harmonic Distortion rate of three phase three level inverter for open loop of SVPWM

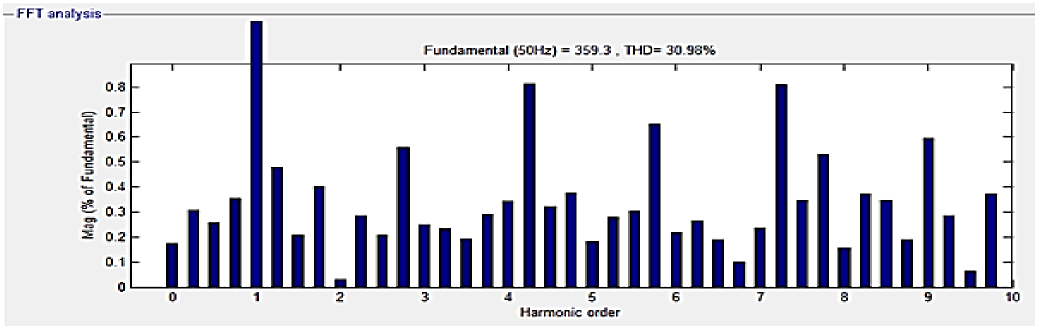

Fig.13 Total Harmonic Distortion of three phase three level inverter for closed loop of SVPWM

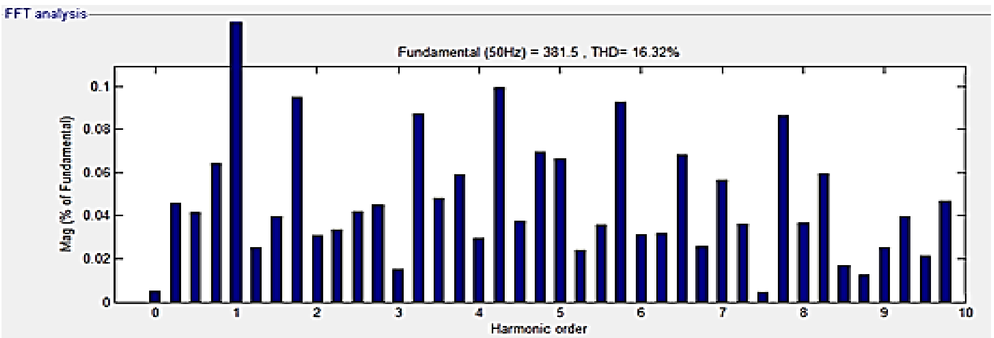

Fig.14 Total Harmonic Distortion of three phase five level inverter for open loop of SVPWM

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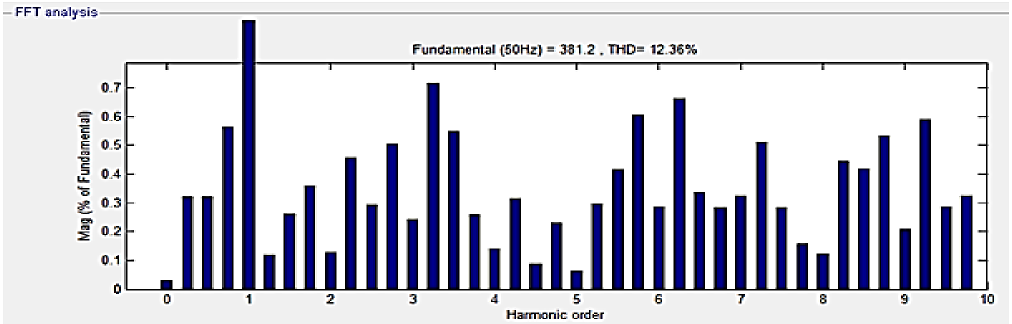

Fig.15 Total Harmonic Distortion of three phase five level inverter for closed loop of SVPWM

VII. CONCLUSION

This paper proves the reduction of THD rate when multilevel inverter is used. Diode clamped inverter topology provides less stress, low harmonics when compared to other topologies. Space vector pulse width modulation is used to control the inverter. The most significant advantages of SVPWM are fast dynamic response and wide linear range of fundamental voltage compared with the conventional PWM. Harmonic distortion rate is low when SVPWM technique is used to control the inverter. Thus, we conclude that the THD rate is low for SVPWM inverter and high level inverter. FLC works simply well than other tracking techniques. FLC avoids the DC/DC chopper. In order to get low THD rate according to applications, multilevel inverter can expand by increasing the number of levels. High-quality output voltage is thus achieved.

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