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Implementation of PV Fed Hybrid Multilevel Inverter using MPPT Based Induction Motor Drive for Industrial Pump Application

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Abstract: This paper shows that versatile stand-alone photovoltaic (PV) systems still demand on at least one battery inverter with improved characteristics of robustness and efficiency, which can be achieved using multilevel topologies. A compilation of the most common topologies of multilevel converters is presented, and it shows which ones are best suitable among the NPC/ Cascaded H-Bridge to implement inverters for standalone applications in the range of a few kilowatts. The harmonics content of the output signals of the both the inverters are analyzed. Two types of harmonics are investigated for induction motors: space harmonics and time harmonics. Space harmonics are generated due to the different phase windings interaction when the power supply is sinusoidal and they can be reduced by applying a proper machine design. Finally a level shifted carrier based pulse width modulation technique is used for MLI. The performance of proposed MLI and cascaded H-Bridge MLI for induction motor drive application is presented. Matlab/Simulink model is developed and simulation results are explained in detail.

Keywords: Induction Motor, Multilevel Inverter, Energy Management, PV Battery, Multilevel SPWM, THD.

I. INTRODUCTION

Now a day's solar power is the quintessential energy source and receiving considerable attention from the researchers. Solar photovoltaic (PV) system generates electricity with advantages such as no pollution, no noise and many more. Solar PV is well suited to remote or arid regions. The constraints due to commutation phenomena are also reduced and each component supports a much smaller fraction of the DC-bus voltage when the number of levels is higher. For this reason, the switches support more high reverse voltages in high-power applications and the converter output signals are with good spectral qualities. Thus, the using of this type of inverter, associated with a judicious control of power components, allows deleting some harmonics [1]. Among the control algorithms proposed in the literature in this field [2-3-4], the SPWM, appears most promising. It offers great flexibility in optimizing the design and it is well suited for digital implementation. It also helps to maximize the available power. The main advantage of multilevel inverters is that the output voltage can be generated with a low harmonics. Thus it is admitted that the harmonics decrease proportionately to the inverter level. For these reasons, the multilevel inverters are preferred for high power applications [5].

However, there is no shortage of disadvantages. Their control is much more complex and the techniques are still not widely used in industry [6]. The traditional inverters are Voltage Source Inverter (VSI) and Current source Inverter (CSI), which consist of diode rectifier front end, DC link and Inverter Bridge. In order to improve power factor, either an AC inductor or DC inductor is normally used. Because of this nature, the Voltage source inverter based PWM VSI and CSI are characterized by relatively low efficiency because

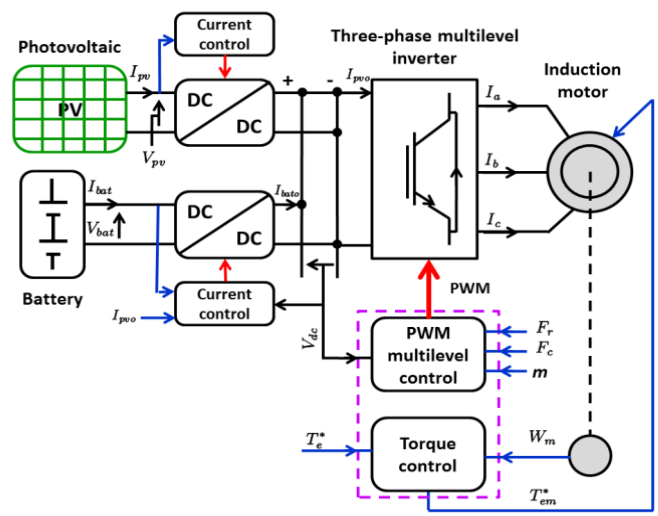


Fig.1. PV Battery standalone system using MLI connected to induction motor.

of switching losses and considerable Electromagnetic Interference (EMI) generation. Many research works are focusing in the development of the efficient control algorithms for high performance variable speed induction motor (IM) drives. Induction motor has been operated as a work horse in the industry due to its easy build, high robustness and generally satisfactory efficiency. Recent development of high speed power semi conductor devices, three phase inverters take part in the key role for variable speed AC motor drives [7]. Traditionally, Three Phase inverters with six switches (SSTP) have been commonly utilized for variable speed IM drives; this involves the losses of the six switches as well as the complexity of the control algorithms and interface circuits to generate six PWM logic signals as shown in Fig.1. So far researchers mainly concentrated on the development of new control algorithms. However, the cost, simplicity and flexibility of the overall drive system which are some of the most important factors did not get that much attention from the researchers. In this a three phase induction motor is connected as load, Which is used in industrial pump applications.

II. PV CELL MODELLING AND MPPT

A PV cell is the basic structural unit of the PV module that generates current carriers when sunlight falls on it. The power generated by these PV cell is very small. To increase the output power the PV cells are connected in series or parallel to form PV module. The equivalent circuit of the PV cell is shown in fig: 2.

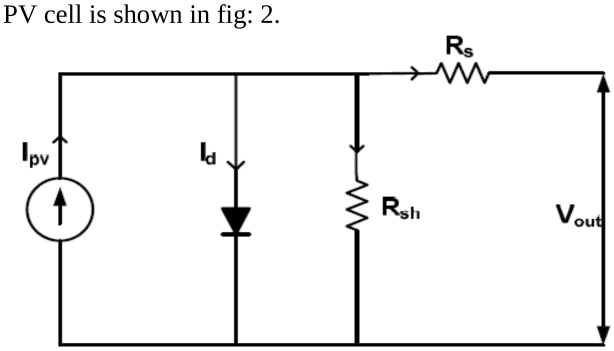


Fig.2. Equivalent circuit of the PV cell.

The main characteristics of the PV cell are given by:

$$I = Ipv - Io\left[e^{\frac{q\,V+IRS}{AKT}} - 1\right] - \frac{V+IRs}{Rsh} \qquad \textbf{(1)}$$

Where,
I_{PV}= Photo-generated current (A)
I= Cell output current (A)
I_0=Diode Saturation Current (A)
V=Cell Output Voltage (V)
R_s=Series Resistor (Ω)
e= Electron Charge 1.6×10-19 (coul)
K=Boltzmann Constant (j/K)
T=cell temperature

The I-V characteristic of a PV module shown in Fig.3 is highly non-linear in nature. This characteristics drastically changes with respect to changes in the solar radiation and temperature. Whereas the solar radiation mainly affects the output current, the temperature affects the terminal voltage. The I-V characteristics of the PV module under varying solar radiation at temperature $T=25^0$ is shown below[12].The data of the PV system used in this are taken from msx60i type of panels.

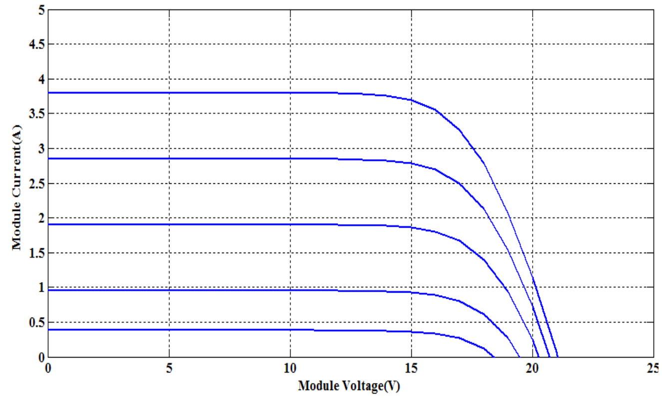


Fig.3. Current versus voltage at constant cell temperature $T=25^0$, irradiation G=100, 250, 500, 750, 1000w/m$^{2.}$

Fig.4 shows the I-V characteristics of the PV module under varying cell temperature at constant solar radiation (1000 W/m^2).

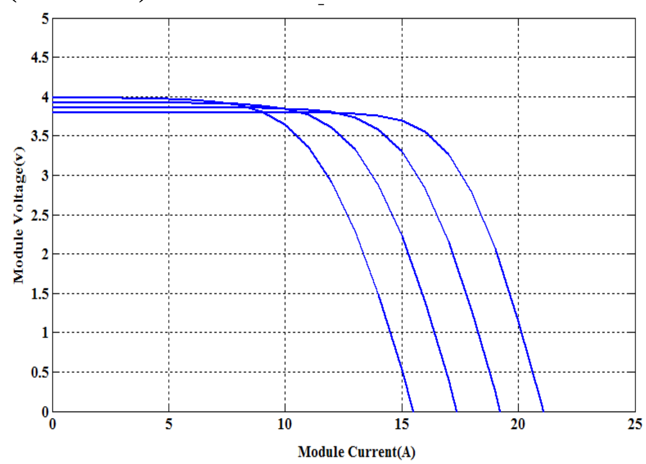


Fig.4. Current versus voltage at constant solar radiation G = 1000 W/m^2,t=25,50,75,100deg cent.

A. Maximum Power Point Tracking (MPPT)

The PV array will be having only one point on its current and voltage characteristics, and that point is called as the Maximum Power Point. The systems which are connected directly will not operate at MPP. So significant amount of enegy is wasted because of this problem. But systems which have a DC-DC converter as a controller to match PV array to Pump set will definitely act at MPP. Several MPPT strategies have been proposed in the past like

- Voltage Reference MPPT
- Perturb and Observe(P&O) MPPT
- Incremental Conductance(INC) MPPT

In this paper Perturb and Observe type of MPPT is used for calculating the Duty Cycle for the DC-DC converter. The flowchart of the MPPT algorithm is shown below in fig. 5.

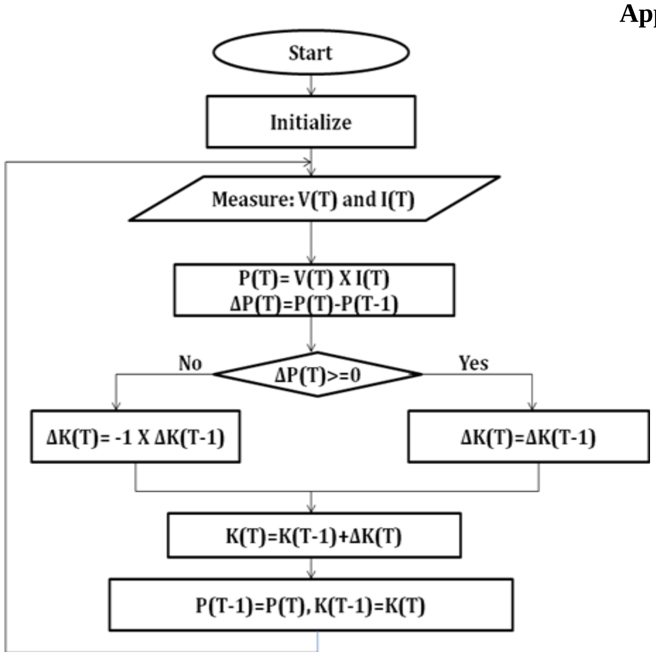


Fig.5. Flow chart of P&O MPPT Algorithm.

The below fig.6 shows the working behavior of P&O based MPPT method.

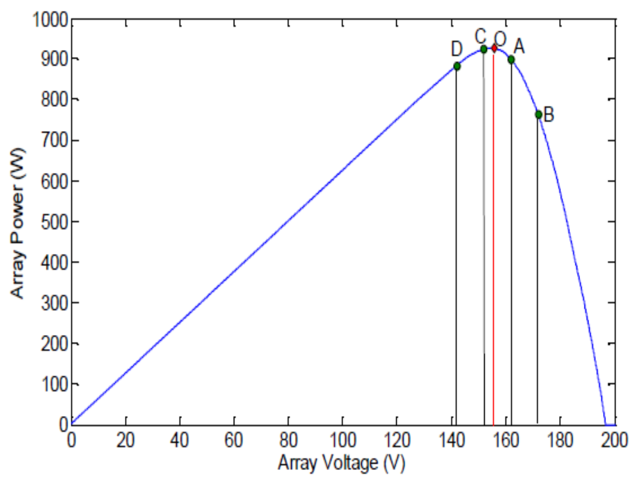


Fig.6. MPPT Tracking.

When compared with the other MPPT algorithms P&O algorithm is simpler to implement and it does not need much knowledge of the previous PV array and details about irradiance and temperature. There are two methods of P&O algorithm

- Reference Voltage Perturbation
- Direct Duty ratio Perturbation

The block diagrams of each method are discussed below fig.7 and fig.8. In the reference voltage control taking the inputs of voltage and current of the PV system, then implementing to MPPT algorithm, the reference PV voltage is found out. The obtained reference voltage is compared with the actual PV voltage and error is given to PI controller to calculate the duty cycle for DC-DC converter.

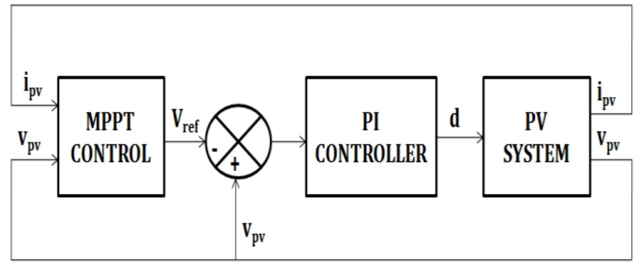


Fig.7. Block Diagram of Reference Voltage based MPPT.

In the Direct Duty Ratio control method the voltage and current inputs from the PV array are taken and the flowchart shown is implemented to calculate the duty cycle for DC-DC converter. When compared with the reference voltage method duty cycle method have several advantages like better stability characteristics and good energy utilization performance.

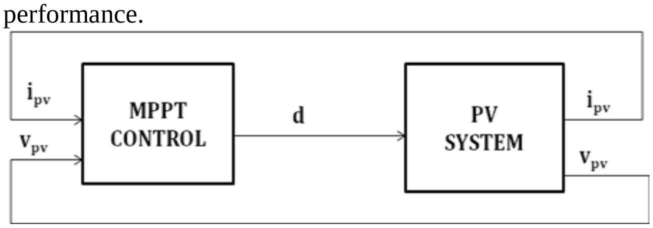


Fig.8. Block Diagram of Direct Duty Ratio based MPPT.

III. MULTILEVEL INVERTER CONTROL STRATEGIES

A. The Three-Level Inverter Control Strategy

Fig. 9 shows a three-phase three-level inverter. It has three arms. Each arm has four switches. Every switch is connected in antiparallel with a diode. This paragraph describes the operation of one of the legs shown at Fig. 10. The voltage Vao between the phase "a" and the neutral point O is defined entirely by the switches position (0 'open' or 1'closed'). Switch sets [S11, S13], and [S12, S14] have complementary positions. When [S11, S13] are open [S12, S14]are closed. The three-level NPC inverter is mostly used [8] for medium-voltage high-power applications. In this converter, the number of commutation sequences (Seq) is equal to 2^4= 16., where 4 stands for the number of switches per arm and 2 is the number of state per switch (0, 1). V_{dc} is the DC-bus voltage. Only three commutation sequences are possible. They are represented at Table 1. Fig. 4 shows the configurations of the inverter's arm which correspond to the three possible commutation sequences:- Sequence 1: S11, S12 conduct and S13 ,S14 open (Fig. 4.a). $V_{a0}=+V_{dc}/2$.- Sequence 2: S12 , S13conduct and S11, S14 open (Fig. 4.b). $V_{a0} = 0$.- Sequence 3: S13 , S14 conduct and S11 ,S12 open (Fig. 4.c). $Va0=-V_{dc}/2$. Sequences 1, 2 and 3 are applied in this order periodically.

A pulse width modulation is used to control the switches. Consider Fig. 11 and Fig.12, the reference voltage V_{ra} is compared to the positive and negative saw tooth carrier V_{cx} and V_{cy} respectively. The comparator output is sent to the switches (Insulated Gate Bipolar Transistor or IGBT) to generate the machine phase voltage. The modulated SPWM voltage has the following characteristics:

- SPWM pulses frequency is the same as the saw tooth carrier f_c. The magnitude is 1 ($f_{SPWM}= f_C$, $|V_{pwm}|=1$)
- The fundamental frequency is controlled by f_r which is the same as the reference voltage where A_r and A_r are the peak to peak value of V_{ao} and V_c respectively frequency.

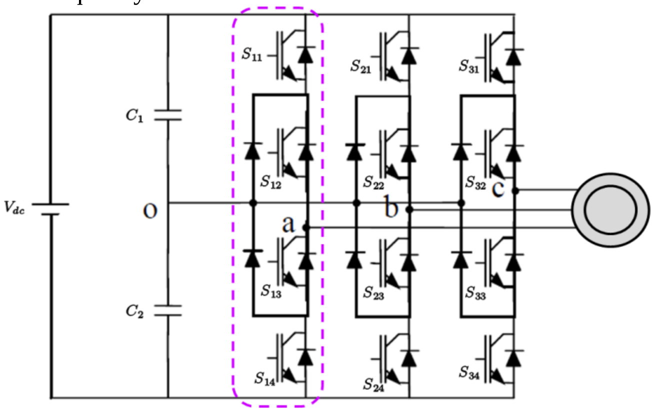
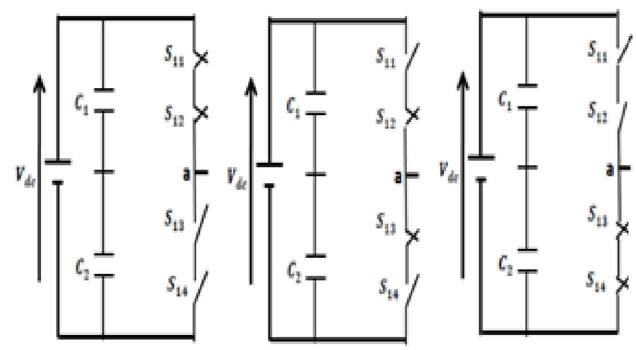


Fig.9. Three-level three phase inverter.



a. Sequence 1 b. Sequence 2 c. Sequence 3

Fig.10. Different possible configurations for one arm.

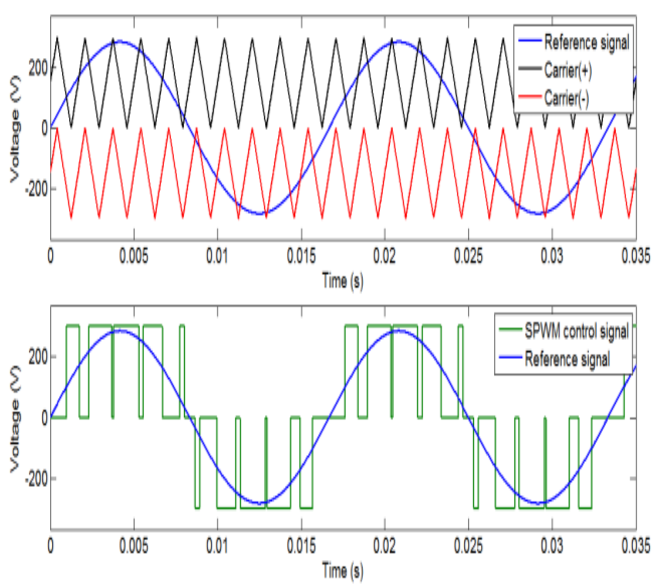


Fig.11. Three-level SPWM control method.

TABLE 1: Sequences of Control Vectors

S.No	[S_{11} S_{12} S_{13} S_{14}]	Vao
01	[1 1 0 0]	Vao
02	[0 1 1 0]	Vao=0
03	[0 0 1 1]	Vao

The inverter output voltages are written as follow (1):

$$Vao = \frac{1}{3}(Vab - Vca)$$
$$Vbo = \frac{1}{3}(Vbc - Vab)$$
$$Vco = \frac{1}{3}(Vca - Vbc) \quad (1)$$

Modulation index (ma) is defined by (2):

$$Ma = \frac{Ar}{(n-1)Ac} \quad (2)$$

B. The Higher Level Inverter Control Strategy

The previous study for the three-level voltage inverter is now extended to higher level inverters. For an n-level inverter, it is possible to determine the number of components that are needed per arm (number of switches, diodes, carrier, etc).

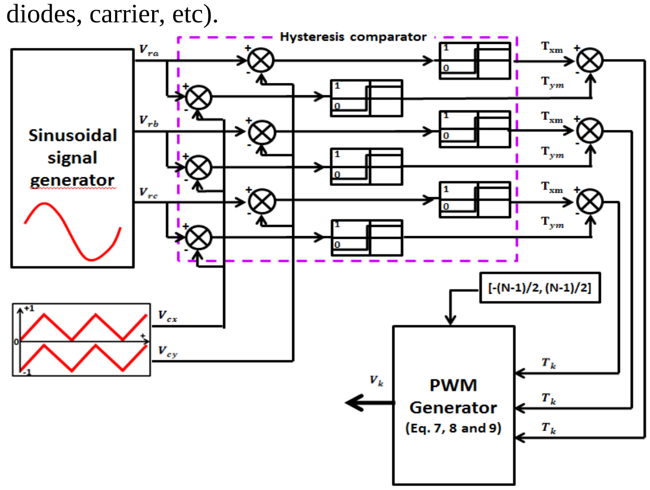


Fig.12. Principle SPWM multilevel inverter control.

Numbers Of Inverter Components Calculation: Define Seq as the number of commutation sequence possibilities. S is the number of secondary voltage sources. K stands for the number of switches per phase. D is the number of diodes loop including the diode switches per phase. C represents the magnitude of the voltage across each capacitor and P is the number of carriers. The following equations provide how these quantities are calculated and table 2 shows the values for several multilevel inverters as shown in Fig.13.

$$Seq = 2^{(n+1)}$$
$$S = P = n - 1$$
$$K = 2(n - 1)$$
$$D = 4n - 6$$
$$C = \frac{Vdc}{n-1} \quad (3)$$

TABLE II: Sequences of Control Vectors

N	Seq	S=P	K	D	C
3	16	2	4	6	Vdc/2
5	64	4	8	14	Vdc/4
7	256	6	12	22	Vdc/6
9	1024	8	16	30	Vdc/8
11	4096	10	20	38	Vdc/10
15	65536	14	28	54	Vdc/14

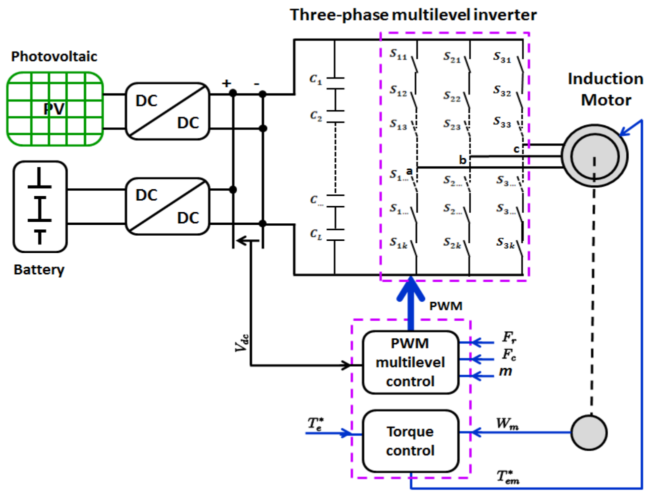


Fig.13. Diagram of the induction motor control principle based on the multilevel inverter.

Calculation Of The Comparator: The comparator uses the reference and carrier signals to generate a binary signal according to the following equation:

$$\begin{aligned} &If\ Vr \geq Vcx => Txm = 1 \\ &If\ Vr < Vcx => Txm = 0 \\ &If\ Vr \leq Vcy => Tym = 1 \\ &If\ Vr > Vcy => Tym = 0 \end{aligned} \quad (4)$$

Where matrices T_{xm} and T_{ym} are the comparator output.

Calculation Of The Adder: The parameter takes the difference between T_{xm} and T_{ym}. It is therefore calculated as follows.

$$Tk = Txm - Tym \quad (5)$$

Calculation Of Inverter Control Vectors: The generation of the pulse vector that controls the inverter is very important. The pulse vector can be generated by applying the G_n vector for each T_k according equation (8). The inverter output voltage V_k is given by equation (9).

$$If\ Tk = \frac{n-1}{2} - i => \begin{Bmatrix} G1 = [0..0\ 1..1] \\ G2 = [1..0\ 0..1] \\ G3 = [1..0\ 0..1] \\ \dots\dots\dots \\ Gn = [1..1\ 0..0] \end{Bmatrix} \quad (6)$$

$$Vk = \frac{h-i}{n-1} Vdc \quad (7)$$

Where $h = \frac{n-1}{2}, i = \{0, 1, 2, \dots\dots\dots, n-1\}$

and Gn is 1x2(n-1) vector. It contains 1x(n-1) zero vector and 1x(n-1) ones vector.

IV. CASCADED H-BRIDGE MULTILEVEL INVERTER

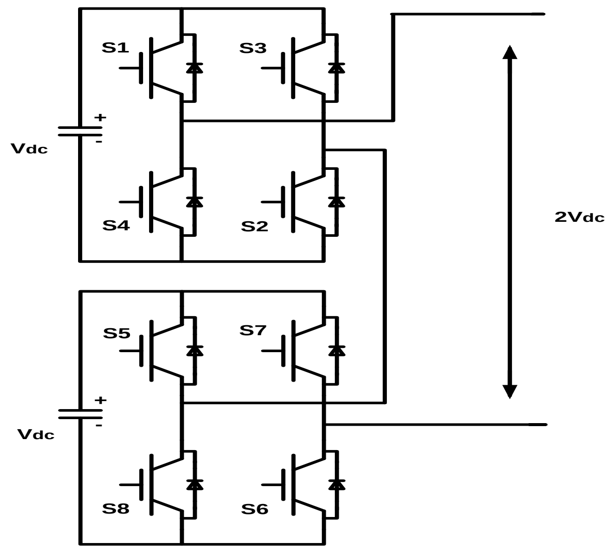


Fig.14. Block diagram of 5-level CHB inverter model.

Multilevel inverters have the capability to deliver higher output power with lower d_v/d_t or lower d_i/d_t and with less-distorted output waveforms, resulting in reduction of electromagnetic interference (EMI) noise and size of an output filter. In distributed-power-generation application, as most renewable energy sources, such as photovoltaic systems, deliver dc power; the generated power must be converted to ac power and is fed into the grid through grid-connected inverters as shown in Fig.14. The number of output voltage levels of CHB is given by 2_{n+1} and voltage step of each level is given by $V_{dc}/2_n$, where n is number of H-bridges connected in cascaded. The switching mechanism for 5-level CHB inverter is shown in Table-3.

TABLE III: Switching Sequence for 5-Level CHB Inverter

Switching States	Levels
S1, S2	V_{dc}
S1,S2,S5,S6	$2V_{dc}$
S4,S2,S8,S6	0
S3,S4	$-V_{dc}$
S3,S4,S7,S8	$-2V_{dc}$

V. PWM TECHNIQUES FOR CHB INVERTER

The most popular PWM techniques used for CHB inverter are 1. Phase Shifted Carrier PWM (PSCPWM), 2. Level Shifted Carrier PWM (LSCPWM).

Case-1: Phase Shifted Carrier PWM (PSCPWM)

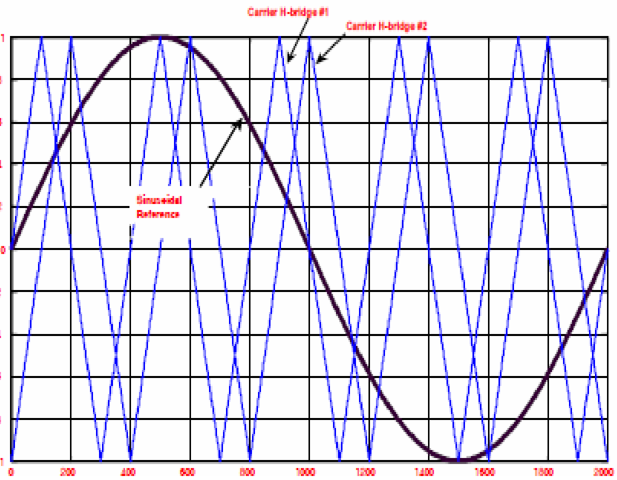


Fig.15. Phase Shifted Carrier PWM.

Fig.15 shows the PSCPWM. In general, a multilevel inverter with m voltage levels requires (m–1) triangular carriers. In the PSCPWM, all the triangular carriers have the same frequency and the same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by $\varphi_{cr}=360^0/(m-1)$. The modulating signal is usually a three-phase sinusoidal wave with adjustable amplitude and frequency. The gate signals are generated by comparing the modulating wave with the carrier waves. It means for five-level inverter, four triangular carriers are needed with a 90° phase displacement between any two adjacent carriers. In this case the phase displacement of $V_{cr1} = 0°$, $V_{cr2} = 90°$, $V_{cr1-} = 180°$ and $V_{cr2-} = 270°$.

Case-2: Level Shifted Carrier PWM (LSCPWM)

The frequency modulation index is given by

$$Mf = f_{cr} / f_{m.} \quad \textbf{(8)}$$

Where f_m is modulating frequency and f_{cr} are carrier waves frequency. The amplitude modulation index 'm_a' is defined by

$$Ma = V_m / V_{cr}\ (m\text{-}1)\ \text{for}\ 0 \leq m_a \leq 1 \quad \textbf{(9)}$$

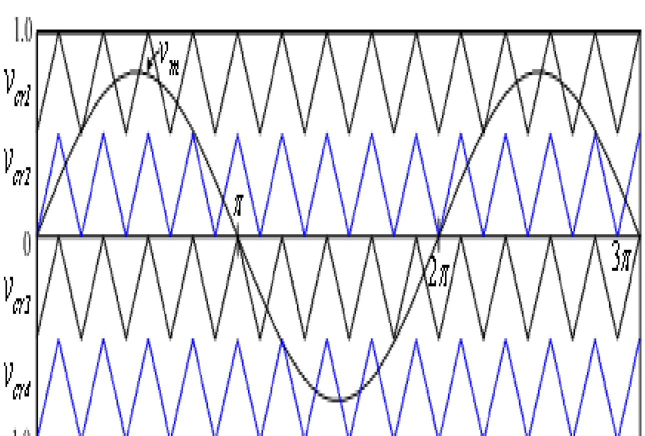


Fig.16. Level shifted carrier PWM (IPD).

Where V_m is the peak value of the modulating wave and V_{cr} is the peak value of the each carrier wave [9]. The amplitude modulation index, m_a is 1 and the frequency modulation index, m_f is 6. After comparing, the output signals of comparator are transmitted to the IGBTs as shown in Fig.16.

VI. MATLAB/SIMULINK RESULTS

The below fig.17 shows the simulation circuit designed to validate the proposed concept of DC-DC converter.

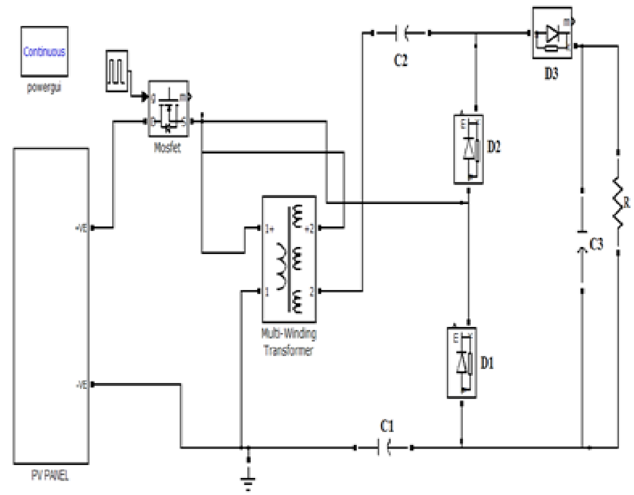


Fig.17.Matlab/Simulink circuit of proposed converter.

The below fig.18 show that the proposed converter with an input voltage of 30v from the PV source gave an output voltage of 400v dc.

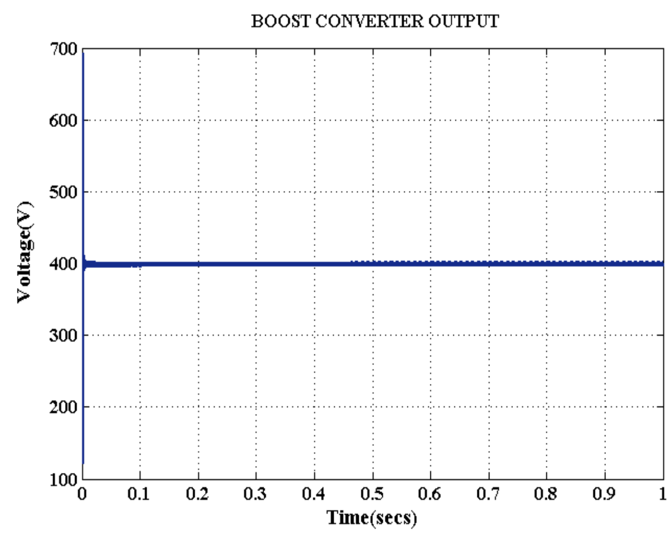


Fig.18. Output voltage of the safety d.

Here simulation is carried out in two different configurations, 1). Implementation of Proposed Concept using Neutral Clamped Type Multilevel Inverter. 2). Implementation of Proposed Concept using Cascaded H-Bridge Multilevel Type Inverter.

Case 1: Implementation of Proposed Concept using Neutral Clamped Type Multilevel Inverter.

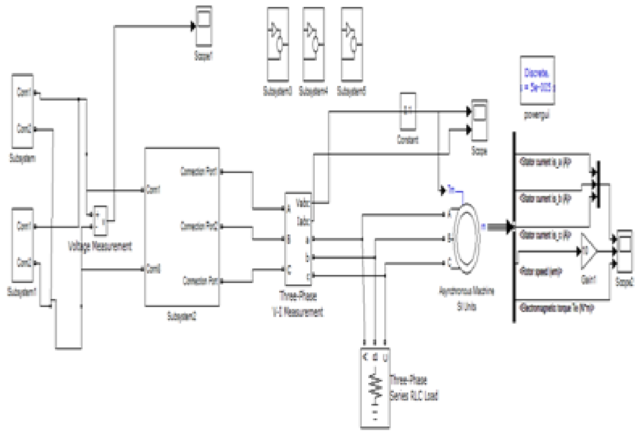


Fig. 19. Matlab/Simulink Model of Proposed NPC Converter with Induction Machine Drive.

Fig.19. shows the Matlab/Simulink Model of Proposed NPC Converter with Induction Machine Drive.

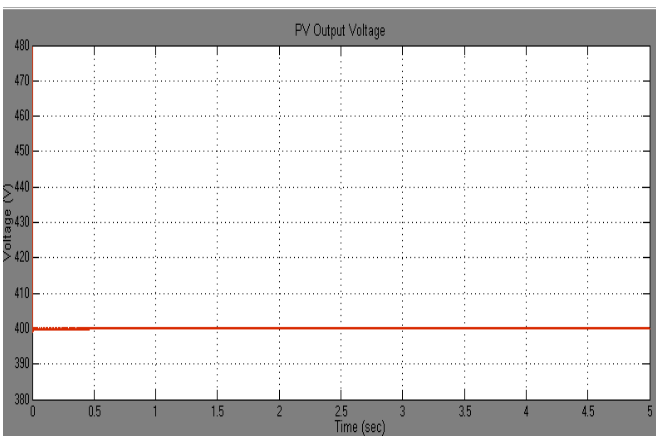


Fig.20. PV Output Voltage.

Fig.20 Output Voltage coming from PV arrays with the help of high step up DC/DC Converter and directly fed to our proposed inverter.

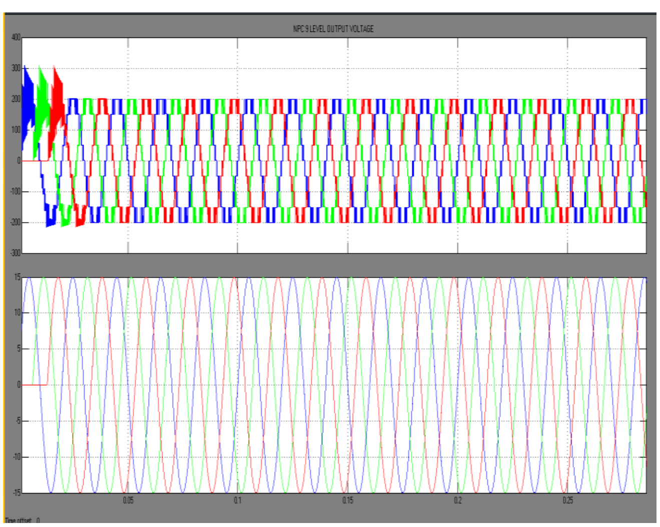


Fig.21. 9-Level Output Voltage and Current.

Fig.21 shows the 9-Level Output Voltage and current coming from the proposed NPC multilevel inverter.

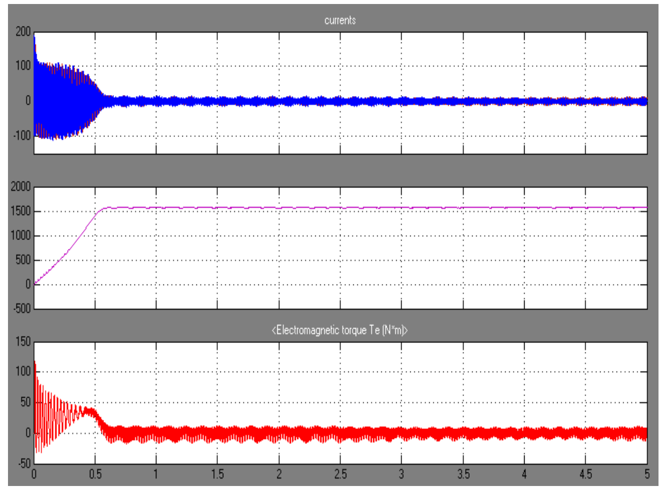


Fig.22. Stator Currents, Speed, Electromagnetic Torque.

Fig.22 shows the Stator Currents, Speed, and Electro-magnetic Torque of the proposed NPC Strategy Controlled Drive Performance Characteristics.

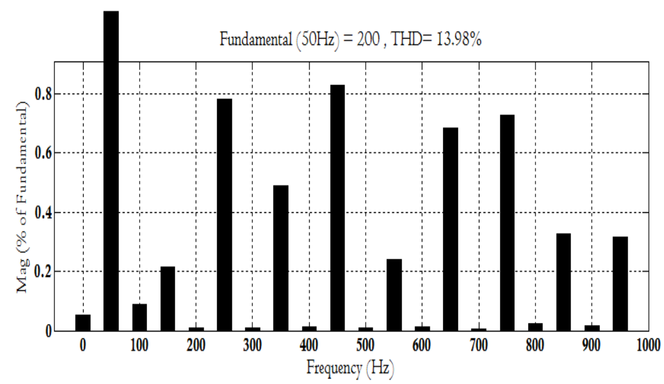


Fig.23. FFT Analysis of Proposed 9-Level NPC Converter Output Voltage.

Fig.23 shows the FFT Analysis of Proposed 9-Level NPC Converter Output Voltage, we get 13.98% no need of any filter we get this value.

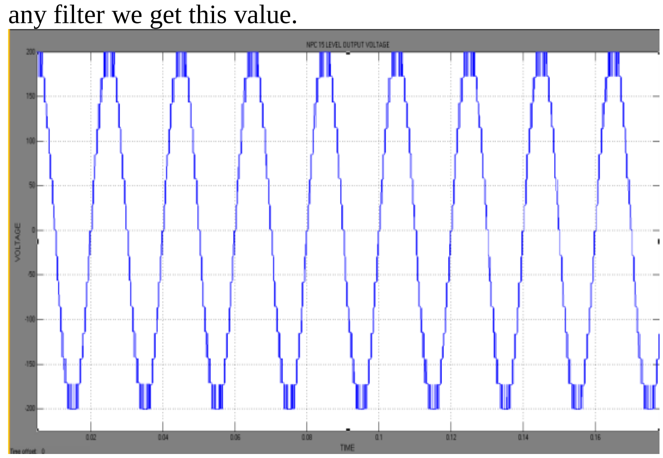


Fig.24. 15-Level Output Voltage.

Fig.24 shows the 15-Level Output Voltage coming from the proposed NPC multilevel inverter.

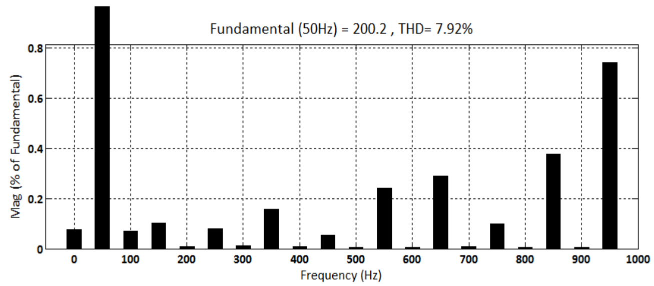


Fig.25. FFT Analysis of Proposed 15 level NPC Converter Output Voltage.

Fig.25 shows the FFT Analysis of Proposed 15 Level NPC Converter Output Voltage, we get 7.92% no need of any filter we get this value.

Case 2: Implementation of Proposed Concept using Cascaded H-Bridge Multilevel Type Inverter.

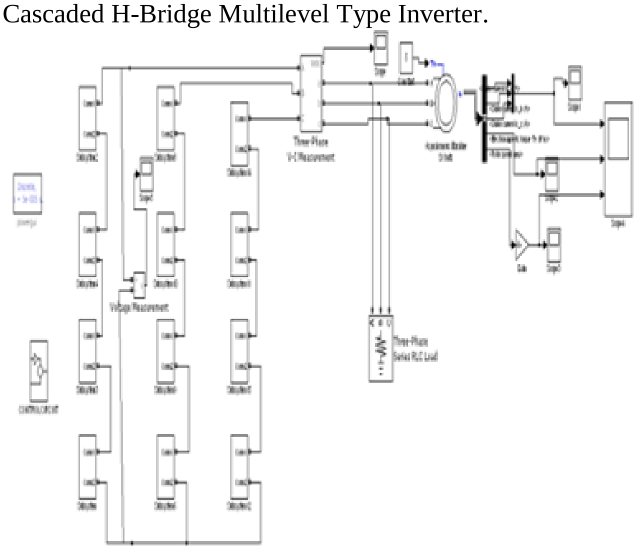


Fig.26. Matlab/Simulink Model of Proposed Cascaded H-Bridge Multilevel Converter with Induction Machine Drive.

Fig.26 shows the Matlab/Simulink Model of Proposed Cascaded H-Bridge Multilevel Converter with Induction Machine Drive.

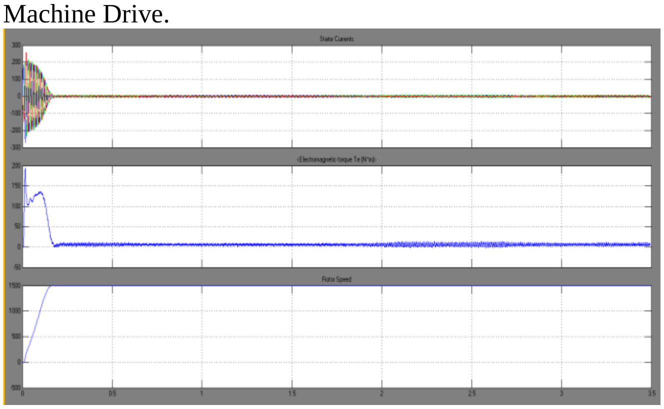


Fig.27. Stator Currents, Speed, Electromagnetic Torque.

Fig.27 shows the Stator Currents, Speed, and Electromagnetic Torque of the proposed 9-Level CHB Multilevel Inverter to Controlled Drive Performance Characteristics.

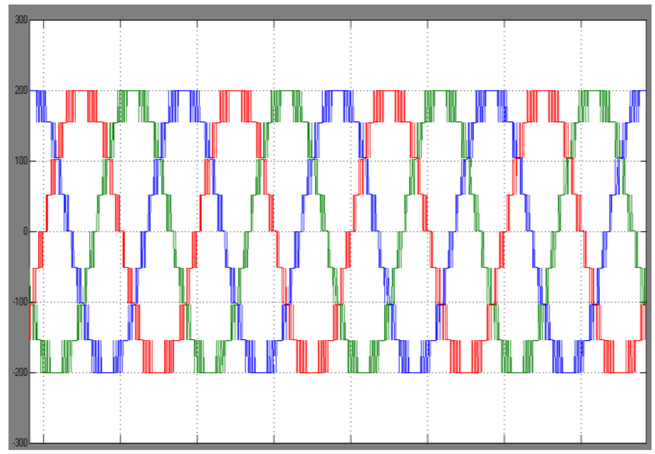


Fig.28. 9- Level Output Voltage.

Fig.28 shows the 9-Level Output Voltage and coming from the proposed CHB Multilevel Inverter.

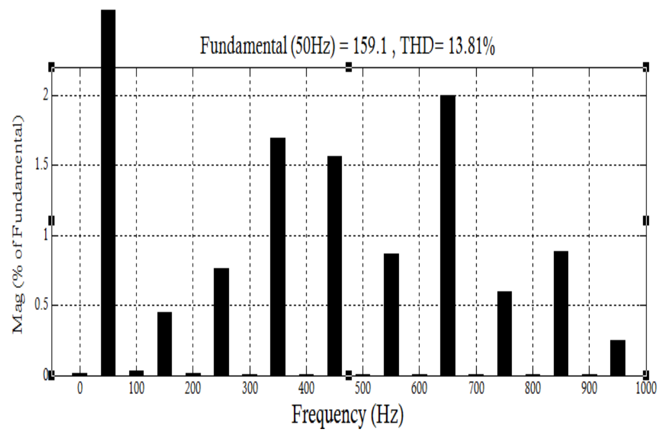


Fig.29. FFT Analysis of Proposed CHB 9-Level Multilevel Converter Output Voltage.

Fig.29 shows the FFT Analysis of Proposed CHB Multilevel Converter Output Voltage, we get 13.81% no need of any filter we get this value.

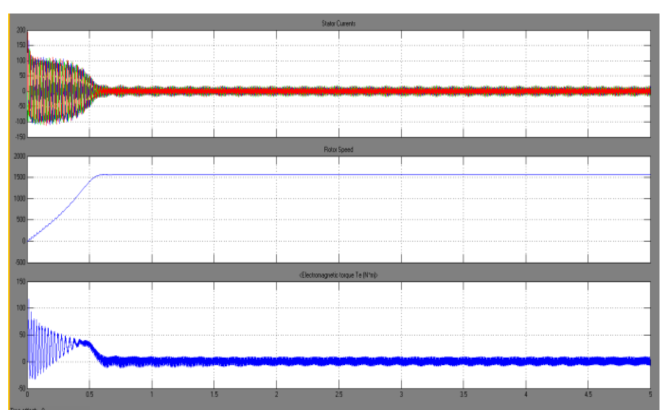


Fig.30. Stator Currents, Speed, Electromagnetic Torque.

Fig.30 shows the Stator Currents, Speed, and Electro-magnetic Torque of the proposed 15-Level CHB Multilevel Inverter to Controlled Drive Performance Characteristics.

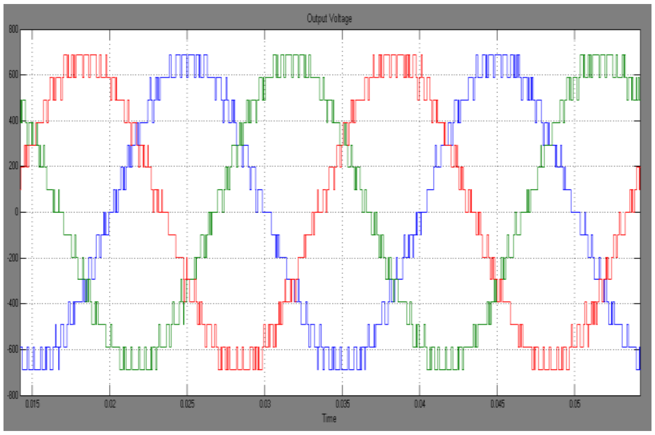


Fig.31. 15- Level Output Voltage.

Fig.31 shows the 15-Level Output Voltage and coming from the proposed CHB Multilevel Inverter. Fig.32. FFT Analysis of Proposed CHB 15-Level Multilevel Converter Output Voltage.

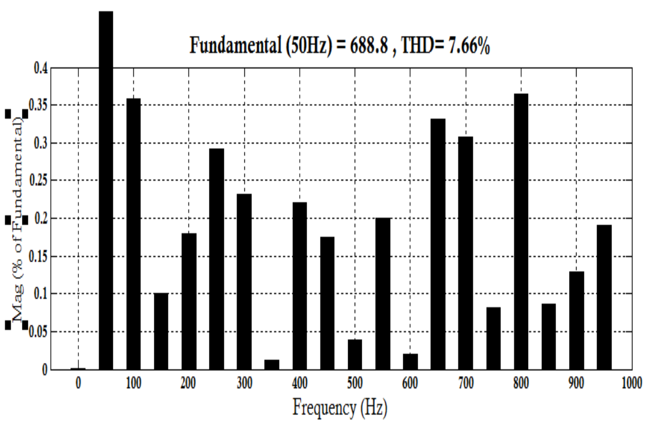


Fig.32. shows the FFT Analysis of Proposed 15-Level CHB Multilevel Converter Output Voltage, we get 7.66% no need of any filter we get this value.

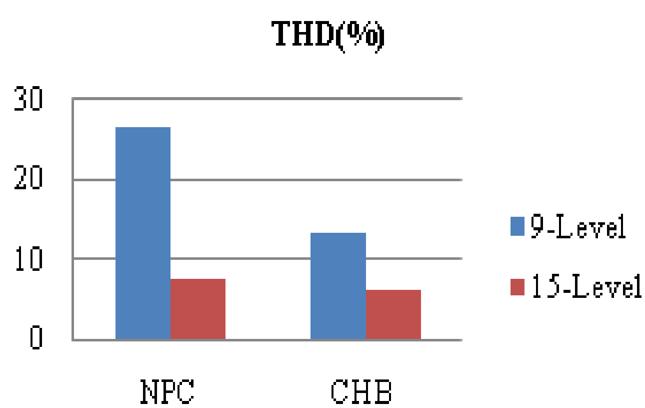


Fig.33. THD Analysis of different Multilevel Inverter Topologies using Bar Graph methodology.

Fig.33 shows the THD Analysis of different Multilevel Inverter Topologies using Bar Graph methodology.

VII. CONCLUSION

In this paper, a general multilevel SPWM control algorithm for 9-level & 15-Level inverters has been modelled and simulated using Matlab/Simulink with different topologies. This algorithm can generate automatically SPWM pulses for any level of inverter by changing only a parameter n which is the number of inverter level. Proposed NPC topology and CHB Multilevel Converter is connected to induction motor has been performed to check the performance characteristics of drive and THD analysis is analysed. The system is supplied by a PV panel and batteries bank. That gives energy autonomy to the system. Simulation results give a better quality of stator current in terms of low harmonics, thus reducing the adverse effects on of the machine life and eventually the electrical network which supplies it, and reduces the switch count, gate drive circuits, low switching losses, etc, in comparison of NPC & FC CHB have no need of any clamping diodes and balancing capacitors, system size may goes to reduces and more efficient.

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