

Cascaded Multilevel Inverter with Voltage Reference Control Method

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Abstract— In multilevel inverters cascaded inverters are more suited for high voltage application. Asymmetrical cascaded inverters enable higher output voltages reduction in size and weight. Based on the application, DC input side of the inverter may be several solar/PV sources or a single DC source. In this paper each of the cascaded H-Bridges are connected to individual DC sources which are provided from a single source with the aid of a transformer and diode rectifiers to get the desired DC voltages and controlling of switches are done by analog controller using voltage amplitude reference method.

Index Terms— Cascaded Multilevel Inverter, Switching Voltage Reference Method, Harmonic Distortion.

I. INTRODUCTION

In multilevel inverter cascaded inverter configuration attracts more research attention than flying-capacitor and diode clamped due to their circuit simplicity and modularity. The number of levels in output voltage can be increased either by increasing the number of H-Bridges or by providing different sources (Asymmetrical configuration) with particular voltage ratio among bridges or combination of both. Increasing number of H-Bridges make the circuit bulky and complex, providing different voltage sources with suitable number of bridges with particular voltage ratio provide required number of output voltage level with circuit modularity. In solar and photo voltaic application each H-Bridge can be powered from individual sources are convenient but for electric vehicle, extracting of sources for each H-Bridge from single AC-source will reduce cost and complexity.

In this work a 15-level inverter with single ac source is simulated in MATLAB model. The controlling of switches enable through voltage reference method. This method transforms the switching angles to switching reference voltage and these reference points are compared with a sinusoidal waveform of fundamental frequency (50Hz) and required amplitude to get the switching points. These pulses are then given to the switches with the help of a Matlab program written (MATLAB function).The control by switching reference voltage method is easy in reducing harmonics and to achieve dynamic control of the inverter output voltage. The proposed control has the following advantages.

1. The proposed method avoids the complex method of calculating switching angles of cascaded multilevel inverters. The method obtains the switching angles based on the required switching reference voltages of the inverter switches and reduce the distortion of inverter output voltage.
2. The conventional cascaded inverters control the amplitude of output voltage by adjusting the conducting angles.

However it is difficult to achieve accurate voltage control for wide range of modulation index since the calculation of conducting angles is nonlinear and complex.

II. STRUCTURE OF 15-LEVEL CASCADED INVERTER

Cascaded inverter consist of several H-Bridges connected in series, these bridges are operated in such a way to get desired output voltage levels. If the sources provided to H-Bridges are different then configuration is said to be Asymmetrical. General Asymmetrical configurations of bridge connection are shown in figure1 Asymmetrical configuration with increased output voltage levels result in improved resolution in output waveform and reduced harmonic content and filtering efforts. In asymmetrical configuration binary and ternary arrangements are considered for voltage sources among bridges. If the DC sources to bridges are in the ratio that is $V_{dc1}:V_{dc2}:V_{dc3}$ is 1:1:1 then a maximum output level of seven ($2*(1+1+1) + 1 = 7$) can be possible, when it is in the binary ratio 1:2:4 or ternary ratio 1:3:9 the level increases to fifteen (15) and twenty seven (27) respectively. Fig. 1 shows the general asymmetrical cascaded H-bridge configuration, here each H-Bridge consist of four switches S1, S2, S3 & S4, controlling of switches S1S3, S2S4 and S1S2 or S3S4 produce a voltage $+V_{dc}$, $-V_{dc}$ and 0.

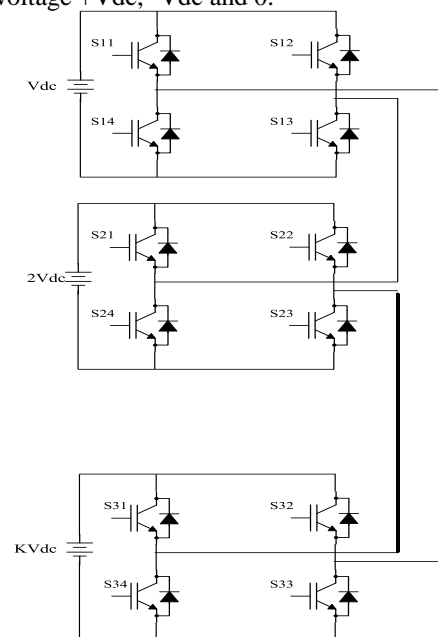


Fig 1. A single phase cascaded 15-level inverter
($V_{dc1}:V_{dc2}:V_{dc3} = 1:2:4$)

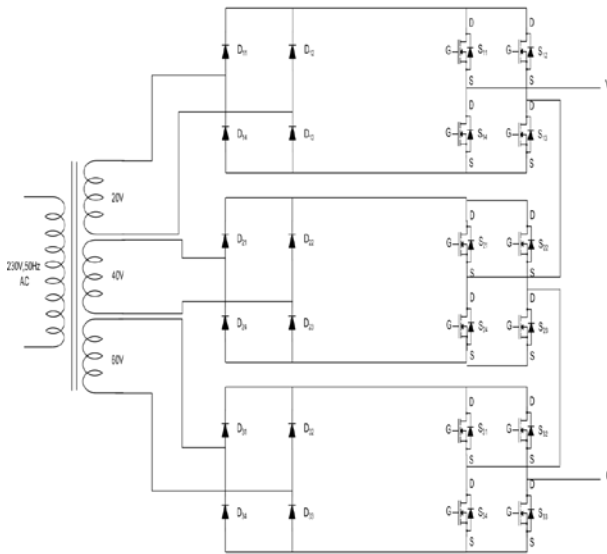


Fig 2. Power circuit for 15-level cascaded multilevel inverter

The output voltage, $V_0 = V_{dc1} + V_{dc2} + V_{dc3}$.

In this project voltage relationship among H-Bridges are in the ratio 1:2:4 that is switching control of inverter modules provide a maximum of 15-level ranges from $-7V_{dc}$ to $+7V_{dc}$ with equal step level of V_{dc} . Different outputs of first bridge are $+V_{dc}$, $-V_{dc}$, 0, similarly second and third bridges are $+2V_{dc}$, $-2V_{dc}$, 0 and $+4V_{dc}$, $-4V_{dc}$, 0 respectively. So switches in each H-Bridge should be controlled in such a way that to obtain desired level in corresponding interval. The table 1 shows the control of inverter modules in the asymmetrical cascaded inverter to produce an output voltage of 15-level, the output voltage ranges from $-7V_{dc}$ to $+7V$. The separate DC sources are provided using a multiple secondary winding transformer and diode rectifiers.

Table 1. Control of inverter modules in the asymmetrical cascaded inverter to produce an output voltage of 15-level

III. DETERMINATION OF CONDUCTION ANGLES

A. Determination using conventional method

In traditional method switching angles are calculated by Fourier series to eliminate 5th, 7th, 11th, 13th harmonics etc. except for fundamental component. Simultaneous equations related to fundamental and harmonics are developed by using Fourier series. To eliminate specified harmonics the related equation is put equal to zero. Conduction angles are determined by solving simultaneous equations. In this 15-level inverter the simultaneous equation are as follows.

$$\begin{aligned} \cos \theta_1 + \cos \theta_2 + \cos \theta_3 + \dots + \cos \theta_7 &= 7M_i & (1) \\ \cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 + \dots + \cos 5\theta_7 &= 0 & (2) \\ \cos 7\theta_1 + \cos 7\theta_2 + \cos 7\theta_3 + \dots + \cos 7\theta_7 &= 0 & (3) \\ \cos 11\theta_1 + \cos 11\theta_2 + \cos 11\theta_3 + \dots + \cos 11\theta_7 &= 0 & (4) \\ \cos 13\theta_1 + \cos 13\theta_2 + \cos 13\theta_3 + \dots + \cos 13\theta_7 &= 0 & (5) \\ \cos 17\theta_1 + \cos 17\theta_2 + \cos 17\theta_3 + \dots + \cos 17\theta_7 &= 0 & (6) \end{aligned}$$

$$\cos 19\theta_1 + \cos 19\theta_2 + \cos 19\theta_3 + \dots + \cos 19\theta_7 = 0 \quad (7)$$

The set of non-linear equation can be solved by using iterative method like Newton-Raphson. This method has merit of eliminating desirable harmonics but it has some problems. The number of simultaneous equations increases with number of level, so does the time and amount of calculations to obtain the conducting angles. Moreover this method is an approximate one depending on the iteration which leads to inclusion of errors. Secondly the conducting angle calculated through offline operation so they have to be arranged in Look-up table. Data in the Look-up table should be more to obtain accurate resolution.

B. The switching reference voltage method

To calculate the conduction angles for a conventional cascaded multilevel inverter, iterative methods such as the Newton-Raphson method is used. This process is complex and time consuming. The proposed method obtains the switching angles by calculating the switching reference voltages of inverter switches that is equal to the output voltage waveform of the multilevel inverter.

In this paper a 15-level cascaded multilevel inverter is studied and the reference voltage waveform is shown in figure 3. The reference voltage can be given as

$$V_{ref} = m * V_{dc} * M_i * \sin(\omega t) \quad (8)$$

Here m is the number of voltage levels of the cascaded inverter during positive half-cycle. In case of a 15-level output voltage m is 7. V_{dc} is the separate dc voltage sources paralleled to H-bridges. For modulation index (M_i) = 1, the reference voltage is expressed as

$$V_{ref} = 7 * V_{dc} * \sin(\omega t) \quad (9)$$

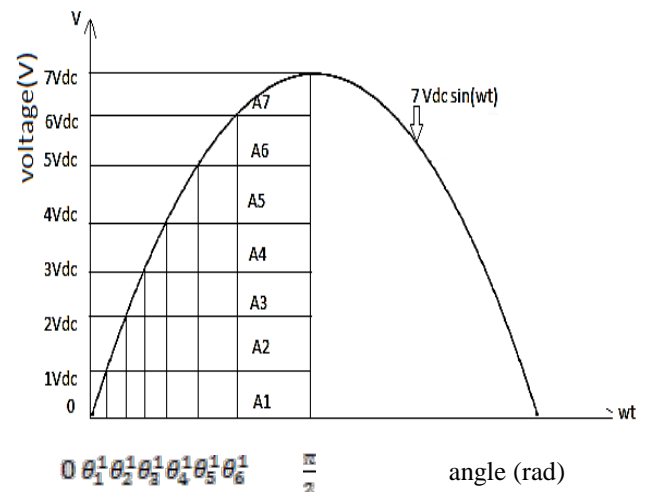


Fig3. Reference Voltage and Step Pulse Area in 15-Level Cascaded Inverter

Fig 3. Shows the reference voltage (V_{ref}) and dummy switching angles (θ_k^1) in case of $M_i=1$. During the positive half cycle, when the reference voltage (V_{ref}) is equal to one if the 7 voltage levels, i.e.: kV_{dc} ($k=1,2,\dots,m-1$), the intersections are defined as dummy angles.

$$\theta_k^1 = \sin^{-1}(k/m), \text{ when } V_{ref} = k \cdot V_{dc}, (k=1,2,\dots,m-1) \quad (10)$$

θ_k^1 : is the intersections of the reference voltage and the output levels of the inverter.

The areas of A_1, A_2, \dots, A_j are surrounded by the reference voltage waveform and the output voltage levels of the cascaded inverter. The area under the reference voltage during the period of $(0-\frac{\pi}{2})$ is the sum of the areas of A_1, A_2, \dots, A_j ($J = 1, 2, \dots, m$). The areas can be obtained as follows.

$$A_1 = \int_0^{\theta_1^1} 7 V_{dc} \sin(wt) d(wt) + \int_{\theta_1^1}^{\pi/2} V_{dc} d(wt)$$

$$A_2 = \int_0^{\theta_2^1} 7 V_{dc} \sin(wt) d(wt) + \int_{\theta_2^1}^{\pi/2} V_{dc} d(wt) - A_1$$

In a similar way, the remaining areas can be calculated. And the generalized equation can be written as follows.

$$A_j = \int_0^{\theta_j^1} m V_{dc} \sin(wt) d(wt) + \int_{\theta_j^1}^{\pi/2} j V_{dc} d(wt) - \sum_{i=1}^{j-1} A_i \quad (11)$$

Figure 4(a) shows the output step-pulse waves in a 15-level cascaded inverter during the period of $(0-\frac{\pi}{2})$ of reference waveform. The real switching angles θ_j ($j = 1, 2, \dots, m$) are the switching control for the inverter modules of cascaded inverter. Since the areas are the same, the real switching angles θ_j can be obtained as:

$$\theta_j = \left(\frac{\pi}{2} - \frac{A_j}{V_{dc}} \right) \quad (12)$$

The switching angles are calculated and used to control the switches of the inverter.

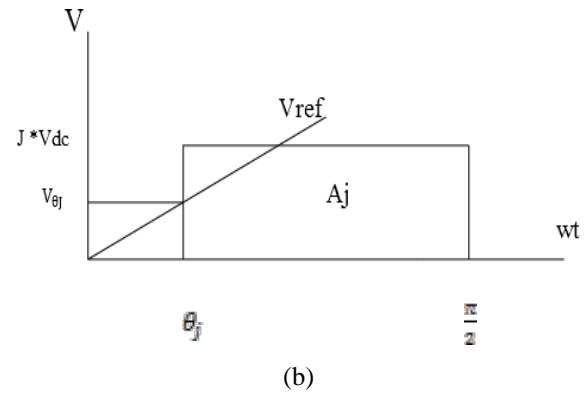
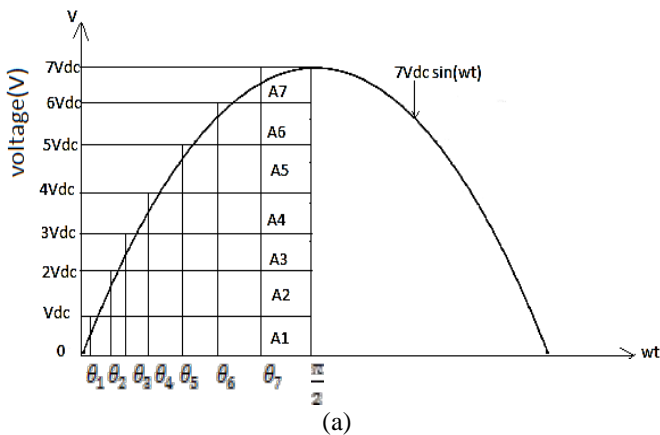


Fig. 4(a) The step pulse waves of output voltage of a 15-level cascaded inverter, (b) The real switching angle and switching reference voltage

For the conventional method, the switching angles θ_j ($j = 1, 2, \dots, m$) are calculated offline for each of the indexes. If the modulation indexes of $(0.1, 0.2, \dots, 1.0)$ are considered, a table of ten switching patterns corresponding to these modulation indexes is stored in the controller. With online method lots of calculations are required if M_i is varied.

Using this proposed method switching angles can be determined in simpler way. In this method it transforms the real switching angles (θ_j) to switching reference voltages (V_{ref}). From the fig 4(b) the point (θ_j, V_{ref}) is the intersection of the vertical line at $wt = \theta_j$ and the reference voltage V_{ref} . The switching reference voltage can be obtained as follows.

$$V_{ref} = V_m \sin(\theta_j), j = 1, 2, \dots, m. \quad (13)$$

The switching control of the cascaded multilevel inverter is made easy. The switching operation of the inverter switches are based on the amplitude of reference voltage waveform, instead of the angles of reference waveform. The switching operation of corresponding switches are activated, if $V_{ref} = V_{ref}$. It is especially advantageous compared to the conventional method. If the modulation index (M_i) is changed from 0.8 to 0.6, then the V_{ref} changed from $5.6V_{dc} \sin wt$ to $4.2V_{dc} \sin wt$ according to (8). It does not need to solve nonlinear equations to obtain the switching angles for different modulation indexes. Furthermore, with this method, a table of only one switching pattern ($V_{ref}, j = 1, 2, \dots, m$) is adequate for cascaded multilevel inverter. The resolution of the output voltage will not be limited, therefore active control of output voltage is easy to achieve. Table 2 shows the conduction angles calculated for the 15-level inverter in terms of voltage amplitude.

Table 2 Conducting angles of 15-level inverter in terms of voltage magnitude

Step	Dummy Angle(rad)	step area	Real switching angle(rad)	voltage amplitude
1	0.14335	1.4992	0.07155	050043
2	0.28973	1.3546	0.21616	1.50134
3	0.44291	1.2052	0.36558	2.50244
4	0.60825	1.0465	0.52426	3.50400
5	0.7956	0.8713	0.69945	4.50657
6	1.02970	0.3644	1.20637	5.5047
7	1.57080	0.3644	1.20637	6.54031

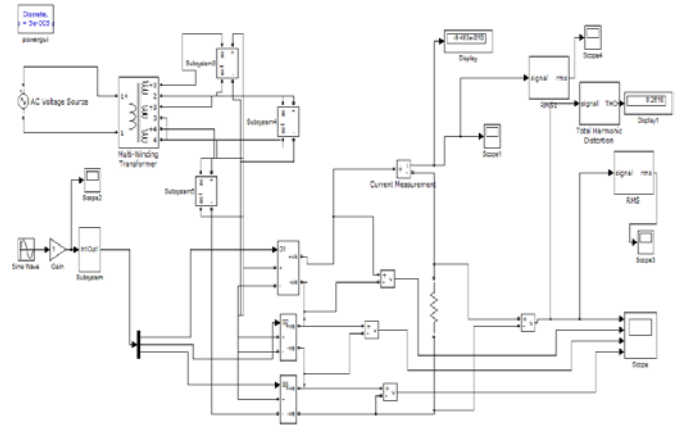


Fig 5 Complete Simulation diagram

IV. SIMULATION AND RESULTS

The proposed 15-level cascaded inverter is simulated by using the MATLAB/SIMULINK software. The parameters used in Simulink model are shown in Table 3. Separate DC sources providing voltages in the ratio 1:2:4 are used. In the case of modulation index (Mi) of the output voltage waveform of the cascaded configuration and the individual H-bridge modules are shown in figure 5. The synthesized output voltage waveform has got 15-levels which approximate an ideal sinusoidal waveform without filters. For the cases of $M_i=0.8$ and $M_i=0.4$, the output voltage waveforms are shown in Fig 6 and Fig 7 respectively

Fig 8 shows the FFT analysis for the 15-level voltage waveform for $M_i=1.0$. The FFT waveform indicates that the low-order harmonics are eliminated and the fundamental component is maximized. However if the number of output voltage levels decrease, the harmonic distortion of output increases.

Table 3 Parameters used in simulation

Parameters	Value
Phase	Single
Frequency	50Hz
Vdc1	10V
Vdc2	20V
Vdc3	40V
Load	Resistive, 100ohm

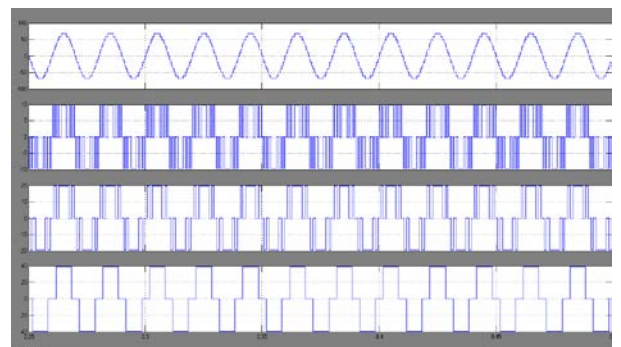


Fig 6 Output voltage waveform of cascaded inverter (Mi=1.0)

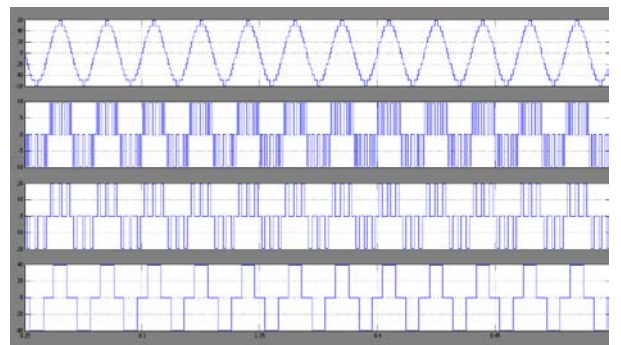


Fig 7 Output voltage waveform of cascaded inverter (Mi=0.8)

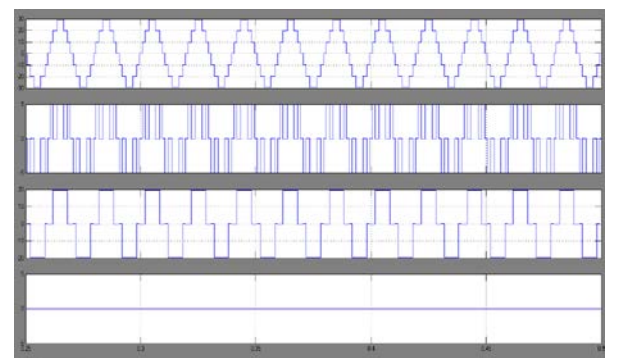


Fig 8 Output voltage waveform of cascaded inverter (Mi=0.4)

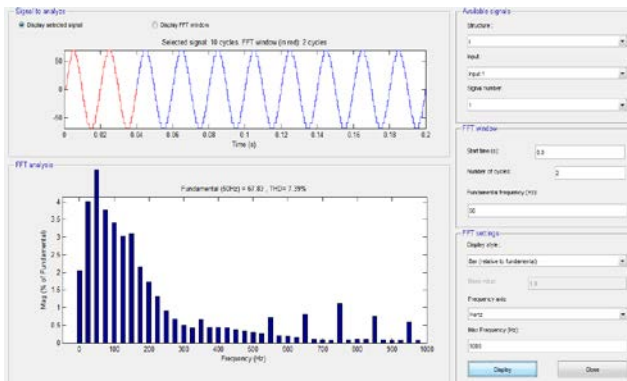


Fig 9 FFT analysis on 15-level output waveform

V. EXPERIMENTAL SETUP AND RESULTS

A. Analog Controller

The proposed 15-level cascaded inverter is controlled using an analog controller using discrete components. From table 1 it can be shown that for a complete cycle the 1st bridge has to provide voltage when output is 10, 30, 50 & 70, similarly 2nd and 3rd bridge output have a magnitude voltage active only when output is 20, 30, 60 & 70 and 40, 50, 60 & 70. Fig 11 shows the realization of analog controller for the three basic pulses to the inverter modules. The overall working of analog controller is shown with the help of a block diagram in Fig 12.

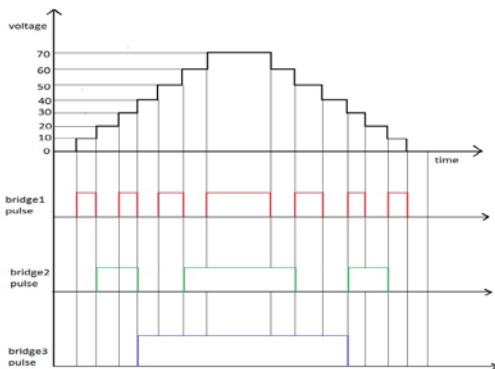


Fig. 10 Three basic pulses to 15-level inverter

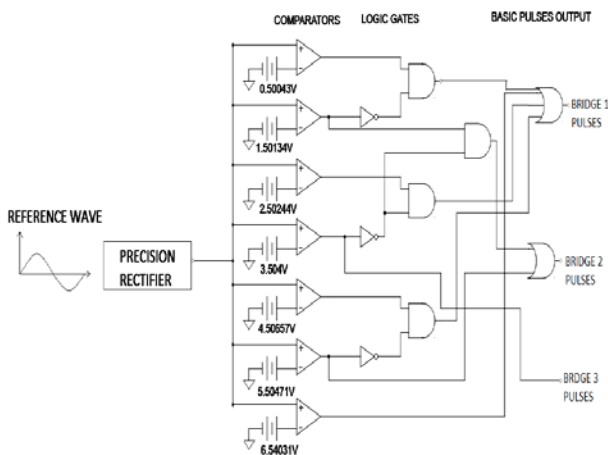


Fig. 11. Analog controller realization circuit using logic gates

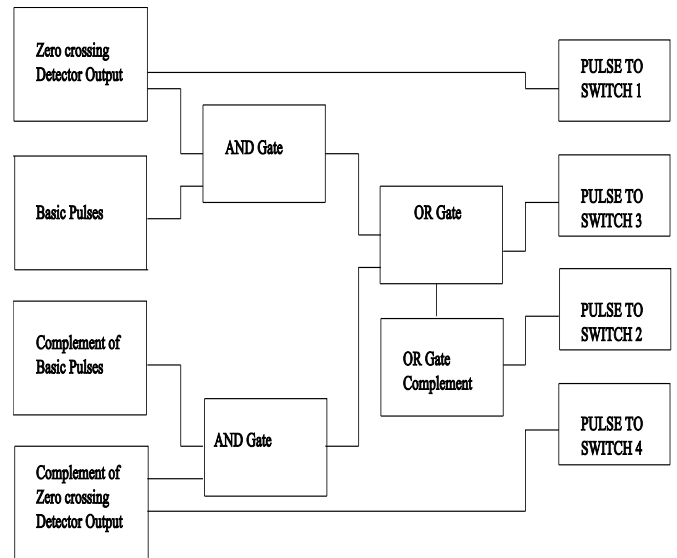


Fig 12 Block diagram model of realization pulses for individual switches

B. Results

The parameters used are the same as given in Table 3. The generated output waveform has got 15 levels as shown in figure 13 and its FFT waveform is analyzed. The harmonics are almost eliminated except for the fundamental component. The experiment and simulation results show that the setup produces a nearly sinusoidal waveform.

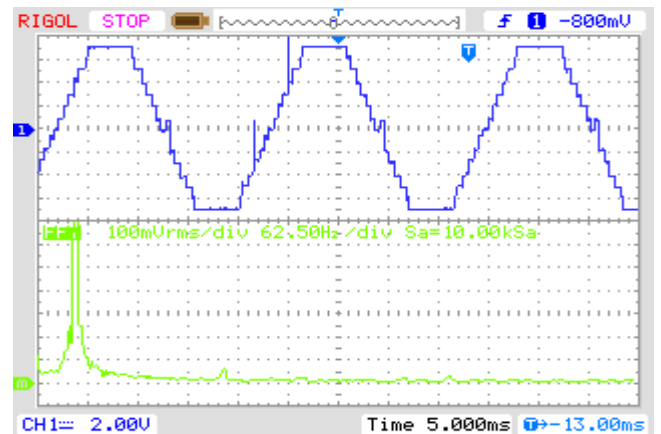


Fig 13 Measured output voltage and FFT waveform

CONCLUSION

In this paper Multilevel inverter is realized with the help of analog controller using voltage reference method. Individual sources to each H-bridge are taken from single source. Complexity and harmonics can be reduced by increasing the number of voltage levels in the output waveform, which can be achieved by suitably selecting voltage relationship among input voltages to the bridge.

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