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Comparative Performance Study of Multilevel H-Bridge Inverters Using Matlab Simulation

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ABSTRACT
The power electronics devices which can converts DC power to AC power at required output voltage and frequency level is known as inverter. Inverter can also be defined as a static power electronics device which converts dc input voltage to ac output voltage with the desired magnitude and frequency. The ideal inverters are expected to have sinusoidal output voltage waveforms. But practically is square wave or quasi square wave. The major classification of inverters is single and multilevel inverters. Multilevel inverter starts with a three level and above. The topology used here is cascaded H-bridge inverter. A multilevel inverter is also being utilized for multipurpose applications, such as static VAR compensators, machine drives for sinusoidal etc. This project is aim at the simulation and comparative performance study of three level, five level and seven level inverters. Total Harmonics Distortion (THD) is a term used to describe net deviation of non-linear waveform from ideal sine waveform features. Total harmonic distortion is the ratio between the RMS value of the harmonics and RMS value of the fundamental. In multilevel inverter as the number of H-bridge increases, the number of A.C output voltage levels increases, THD decreases and that is what we want to compare. When there is variable in H-bridges of a MLI input voltages there will be an increase in THD to compare equal H-bridges of a MLI of the voltage level. Cascaded H-bridge type multilevel inverters are built in MATLAB/SIMULINK software, THD are analyzed in FFT window and the results are illustrated.
Keyword: *Inverter, Bridge, MATLAB, Simulink, Compensator. THD, Harmonic, Fast Fourier Transform*

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I. INTRODUCTION

Multilevel inverters have gained its popularity recently because it satisfies the high-power requirement in an industry due to its advantages of high-power quality waveform and low electromagnetic compatibility. This power converter structure has been introduced as an alternative in high power and medium voltage conditions. A multilevel converter has not only achieved high power rating but also enable the use of renewable energy sources. These renewable energy sources can be photovoltaic, wind and fuel cell which can easily be interfaced to a multilevel converter system for a high-power application. Meanwhile, the basic concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage DC sources to execute the power conversion by synthesize a staircase voltage output waveform. Separate DC sourced full-bridge cells are placed in series to synthesize a staircase AC output voltage in cascaded H-bridge topology.

Capacitors, batteries, and renewable energy voltage sources can be used as the multiple DC sources. Then the commutation of the power switches aggregates these multiple DC sources in order to achieve high voltage at the output, meanwhile the rated voltage of the power semiconductor switches depends on the rating of the DC voltage sources to which they are connected.

Conventional inverters give two level output voltage while multilevel inverter give three or more level output voltages. This multilevel inverter produces a stepped output voltage with reduced harmonic distortion when compared to a conventional inverter and the higher the level of the inverter the lesser the harmonic distortion.

II. METHODOLOGY

A. Design and Methodology of Multilevel Cascaded H Bridge Inverter

Inverters are power converters that convert DC power to AC power and maintain the output voltage and frequency constant. These inverters are mainly classified into two types:

1. Voltage source inverter: Here the output voltage depends on source voltage.
2. Current source inverter: Here the output current depends on source current.

In cascaded H-bridge inverter each switching devices always conduct for half cycle, hence distributing the currents equally among the switching devices. No clamping diodes present and no voltage balancing capacitors present as in neutral point clamped (NPC) and frying capacitor circuit respectively. Separate DC sources eliminate the need

to apply voltage balancing circuits. The converter circuit is based on the series connection of a single-phase inverter with separate Dc sources. The resulting phase voltage is synthesized by the addition of the voltage generated by the different cells.

For the purpose of this project, we will be dealing with voltage source inverter to prove that the more the level of multilevel inverter the lesser the total harmonics distortion (THD) which leads to less power losses and the output voltage produce will be nearer to pure sine waveform.

We use insulated bipolar gate transistor (IGBT) switches because of the advantages it has over other switches in medium and high-power applications.

B. Single Phase Three Level Cascaded H-Bridge Multilevel Inverter:

The list of components in single phase three level cascaded H-bridge multilevel inverter is: single isolated DC source, four IGBT switches and resistive load. The result of output voltage waveform is +Vdc, 0, -Vdc. Note the number of levels is determine by the number of cell (a unit of H-bridge).

m-level=(2H+1) (1)

Where: H= a cell, m= number of levels.

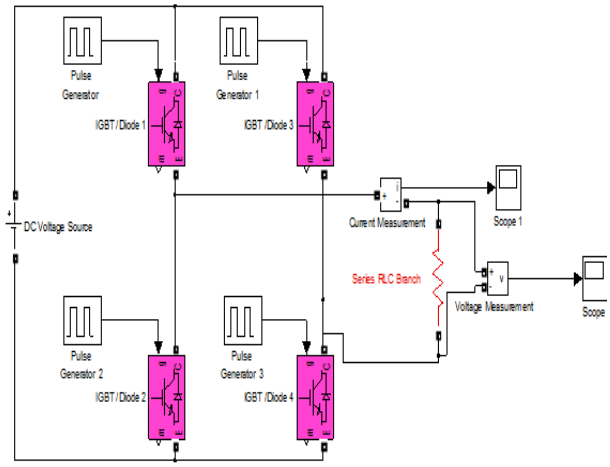
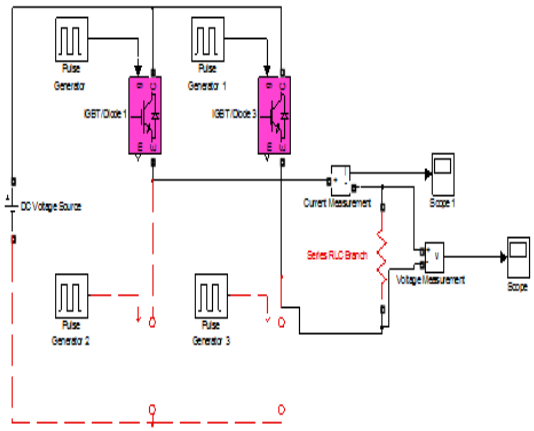


Figure 1. Single phase full bridge inverter

1. MODE OF OPERATION

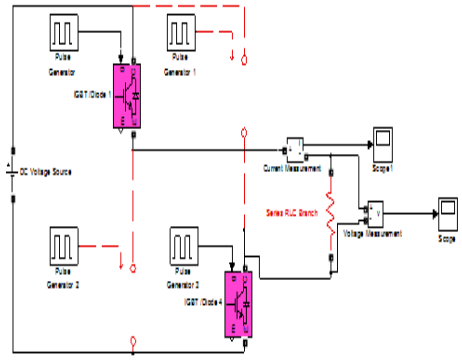
The modes of operation involve single phase full bridge inverter in one full cycle are explained below:

Mode 1:

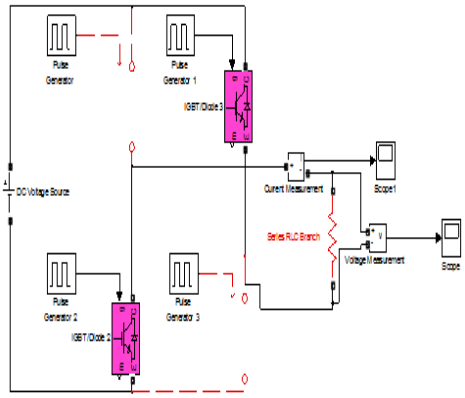


When switches S1 and S3 are turned on, no source voltage is connected to the load. Therefore, the output voltage obtained across the load is zero.

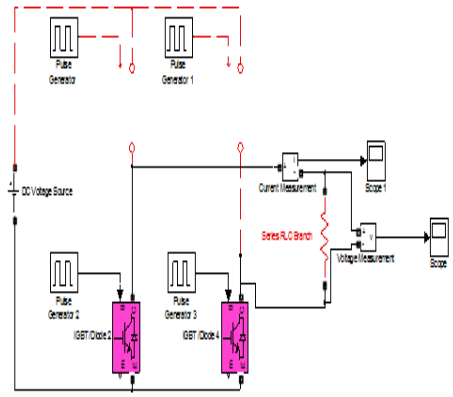
Mode 2:



When switches S1 and S4 are turned on, the output voltage obtained across the load is +Vdc.
Mode 3:



When switches S2 and S3 are turned on, the output voltage obtained across the load is -Vdc.
Mode 4:



When switches S2 and S4 are turned on, the output voltage obtained across the load is zero.
The Table 1 below shows the operated switches and the output voltage across the load.

Table 1: Mode of operation of single-phase full bridge inverter

Mode	Switch(S1)	Switch(S2)	Switch(S3)	Switch(S4)	+Vdc	-Vdc	Output voltage
1	1	0	1	0	0	0	0
2	1	0	0	1	1	0	V
3	0	1	1	0	0	1	-V

2. SWITCHING ANGLE OF A SINGLE-PHASE FULL BRIDGE INVERTER

Switching angle of a full bridge inverter is calculated using Equal phase (EP) method. In the equal phase the switching angles are distributed averagely in the range between 0 to π. The main switching angles are obtained by this formula;

Switching angle (αi) = i x 180/m (2)

Where i =1, 2, 3……. (m-1) /2 and m is the number of voltage level.

Then other switching angles in second, third, and fourth quadrants of sine wave are derived from the main switching angles according to the below

$\alpha 1$ =1 x 180/3 = 60

$\alpha 2$ =2x 180/3 = 120

$\alpha 3$ = 3 x 180/3 = 180

$\alpha 4$ = 4 x 180/3 = 240

$\alpha 5$ = 5 x 180/3 = 300

$\alpha 6$ = 6 x 180/3 = 360

The propose frequency of this project is 50Hz and this imply that 50Hz is equal to 50cycle per second. Then we need to fine time required in 1cycle

50cycles = 1second

1cycle = X second

X (second) = (1cycle x 1second)/50cycles

X = 0.02second.

From the above switching angles and frequency, we can now derive the switching time table

Table 2: Switching time table for single phase full bridge inverter

Pulse	0	V	0	0	-V	0
Switching Angle	60	120	180	240	300	360
Time(second)	0.0033	0.0066	0.0100	0.0133	0.0166	0.02
S1 and S4		On period pulse width (16.66%)				
S2 and S3					On period pulse width (16.66%)	

3. SINGLE PHASE 5-LEVEL CASCADED H-BRIDGE MULTILEVEL INVERTER

The list of components in single phase five level cascaded H-bridge multilevel inverter is: two single isolated DC source (two-unit cells), eight number IGBT switches and resistive load. The result of output voltage waveform is +2Vdc, +Vdc, 0, -Vdc, -2Vdc.

Note that number of levels is determine using this formula: m-level =2H+1.

Where m is the number of levels, H is the full bridge inverter or a cell of inverter.

For examples to fine the number of cells in 5-level inverter

5 = 2H+1; 5 - 1 = 2H; 4 = 2H (3)

H = 4/2 = 2 cells. (4)

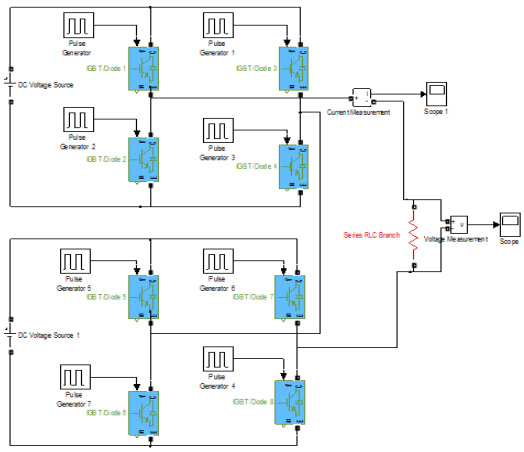
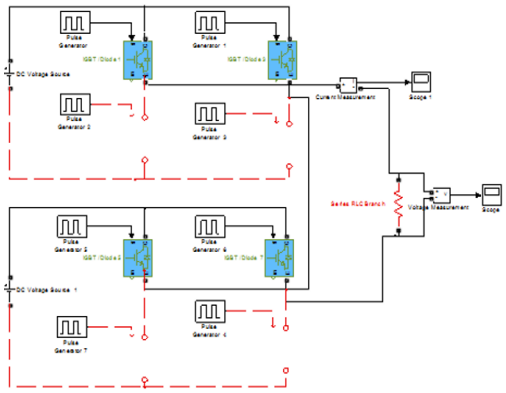


Figure 2: Single phase five level cascaded H-bridge inverter.

4. MODE OF OPERATION OF FIVE LEVEL CASCADED H-BRIDGES INVERTER.

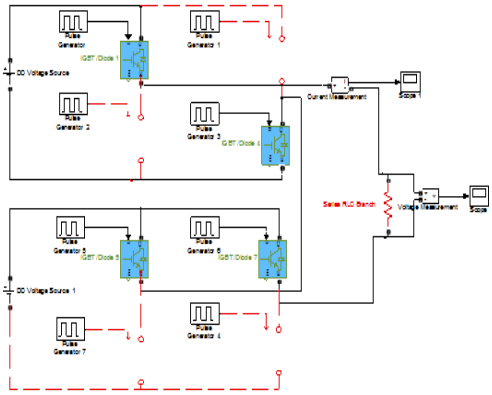
The mode of operation involves in five levels CHB inverter in one full cycle are explained below:

Mode 1:



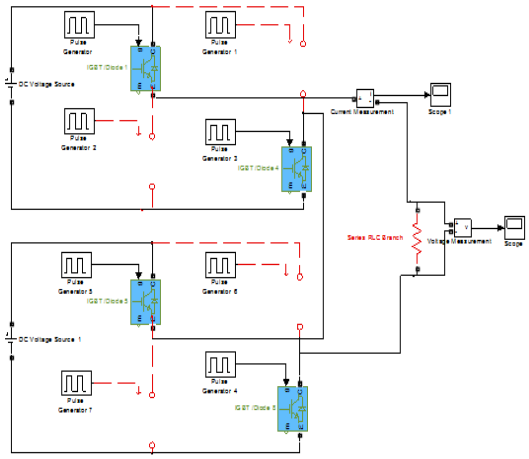
When switches S1, S3, S5 and S7 are turned on, the output voltage obtain will be zero or no source voltage is connected to the load.

Mode 2:



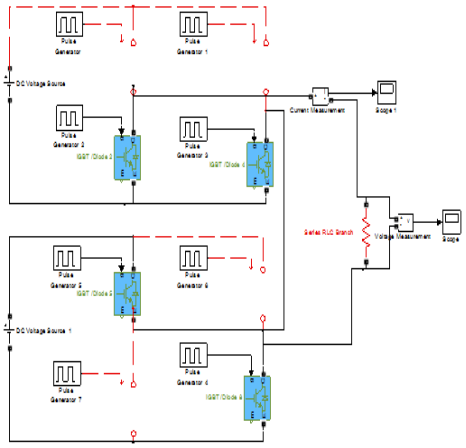
When switches S1, S4, S5 and S7 are turned on, the source voltage connected to the load will be +Vdc1 (i.e. output voltage will +V).

Mode 3:



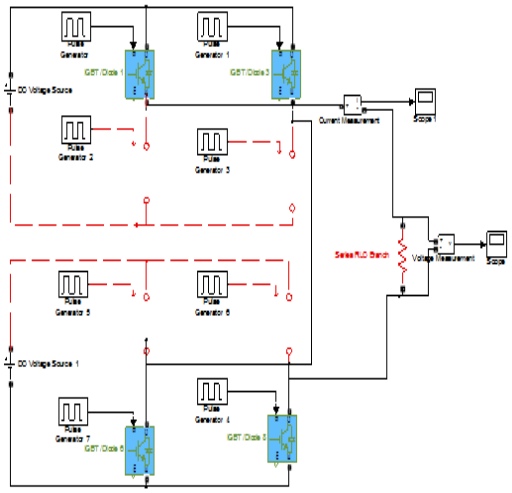
When switches S1, S4, S5 and S8 are turned on, the output voltage across the load will be +Vdc1 + +Vdc2= +2V.

Mode 4:



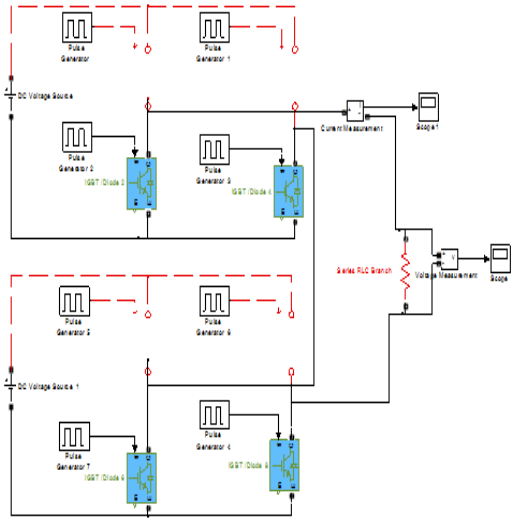
When switches when switches S2, S4, S5 and S8 are turned on, the output voltage will be +Vdc2.

Mode 5:



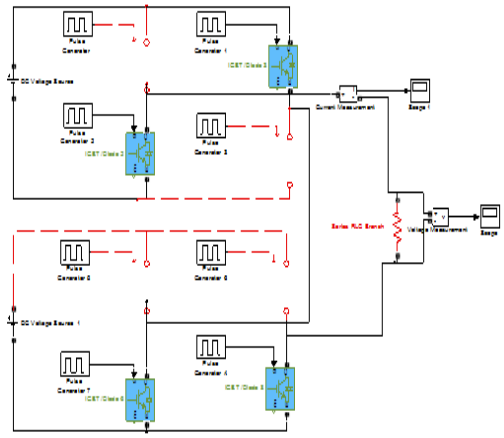
When switches S1, S3, S6 and S8 are turned on, the voltage across the load will be zero (i.e. the output voltage is 0).

Mode 6:

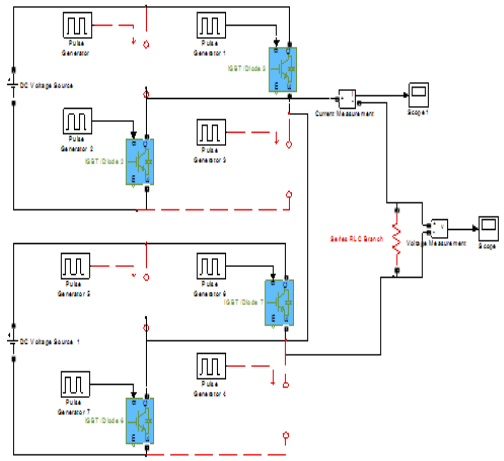


When switches S2, S4, S6 and S8 are turned on, the voltage across the load will be zero.

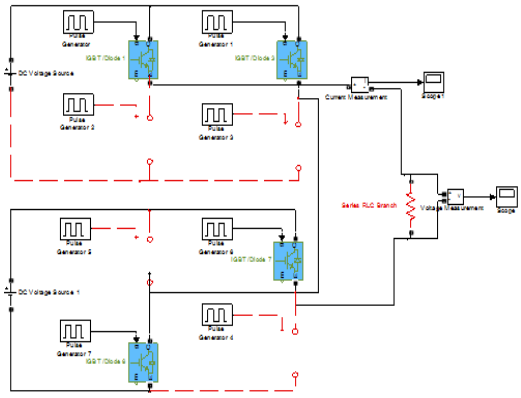
Mode 7:



When switches S2, S3, S6 and S8 are turned on, the voltage across the load will be negative voltage (-Vdc1).
Mode 8:

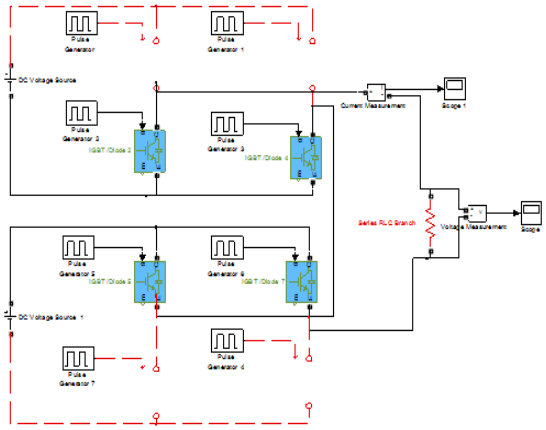


When switches S2, S3, S6 and S7 are turned on, the voltage across the load will be two negative voltage (i.e. -Vdc1 + -Vdc2 = -2V).
Mode 9:



When switches S1, S3, S6 and S7 are turned on, the voltage across the load will be negative voltage (-Vdc2).

Mode 10:



When switches S2, S4, S5 and S7 are turned on, the voltage across the load will be zero (0 volt).

Table 3: Mode of operation involved in a single phase five levels Cascaded H-Bridge inverter.

Mode	S1	S2	S3	S4	S5	S6	S7	S8	Vdc1	Vdc2	Output voltage
1	1	0	1	0	1	0	1	0	0	0	0
2	1	0	0	1	1	0	1	0	1	0	+V
3	1	0	0	1	1	0	0	1	1	1	+2V
4	0	1	0	1	1	0	0	1	0	1	+V
5	1	0	1	0	0	1	0	1	0	0	0
6	0	1	0	1	0	1	0	1	0	0	0
7	o	1	1	0	0	1	0	1	-1	0	-V
8	0	1	1	0	0	1	1	0	-1	-1	-2V
9	1	0	1	0	0	1	1	0	0	-1	-V
10	0	1	0	1	1	0	1	0	0	0	0

7. SWITCHING ANGLE OF A SINGLE PHASE FIVE LEVEL CHB INVERTER:

Switching angle of a single phase five level Cascaded H-Bridge inverter is calculated using Equal phase (EP) method. The switching angles are distributed averagely in the range between 0 to π. The main switching angles are obtained by this formula;

Switching angle (αi) = i x 180/m (5)

Where i =1, 2, 3……. (m-1) /2 and m is the number of voltage level.

Then other switching angles in second, third, and fourth quadrants of sine wave are derived from the main switching angles.

Substituting equation 2 above for calculation of five level switching angles, we have:

$\alpha 1$ = 1 x 180/5 = 36

$\alpha 2$ = 2 x 180/5 = 72

$\alpha 3$ = 3 x 180/5 = 108

$\alpha 4$ = 4 x 180/5 = 144

$\alpha 5$ = 5 x 180/5 = 180

$\alpha 6$ = 6 x 180/5 = 216

$\alpha 7$ = 7 x 180/5 = 252

$\alpha 8$ = 8 x 180/5 = 288

$\alpha 9$ = 9 x 180/5 = 324

$\alpha 10$ = 10 x 180/5 = 360

The propose frequency of this project is 50Hz and this imply that 50Hz is equal to 50cycle per second. Then we need to fine time required in 1cycle

50cycles = 1second

1cycle = X second

X (second) = (1cycle x 1second)/50cycles

X = 0.02second.

From the above switching angles and frequency, we can now derive the switching time table

Table 4: Switching time table for single phase five level CHB inverter.

Pulse no	0	+V	+2V	+V	0	0	-V	-2V	-V	0
Switching angle	36	72	108	144	180	216	252	288	324	360
Time (second)	0.002	0.004	0.006	0.008	0.010	0.012	0.014	0.016	0.018	0.02
S1, S4, S8			On period pulse width (30%)							
S5			(10%)							
S3								(10%)		
S2, S6, S7								On period pulse width (30%)		

V. SINGLE PHASE SEVEN LEVEL CASCADED H-BRIDGE MULTILEVEL INVERTER.

The list of components in single phase seven level cascaded H-bridge multilevel inverter is: three single isolated DC source (three-unit cells), twelve number IGBT switches and resistive load. The result of output voltage waveform is +3Vdc, +2Vdc, +Vdc, 0, -Vdc, -2Vdc, -3Vdc.

Note that number of levels is determine using this formula: m-level =2H+1.

Where m is the number of levels, H is the full bridge inverter or a cell of inverter.

Fine the number of cells in 7-level inverter

$7 = 2H+1;\ 7 - 1 = 2H;\ 6 = 2H$ (6)

H=6/2=3cells

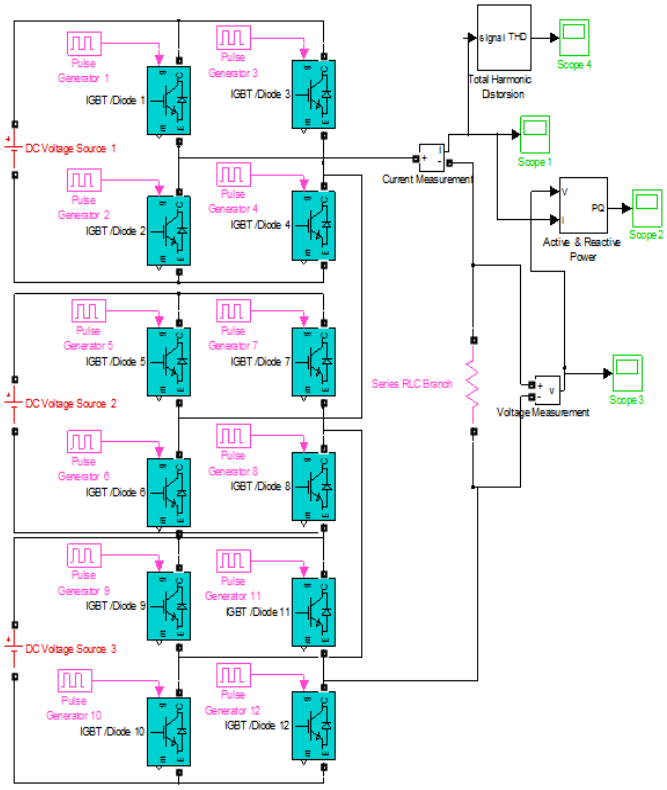
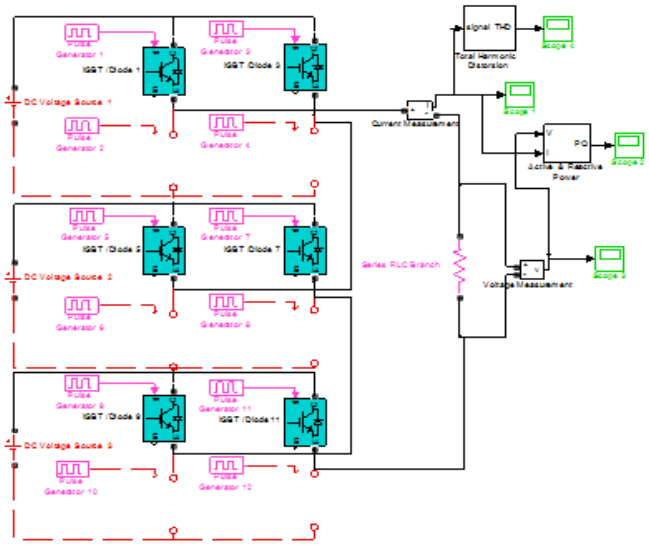


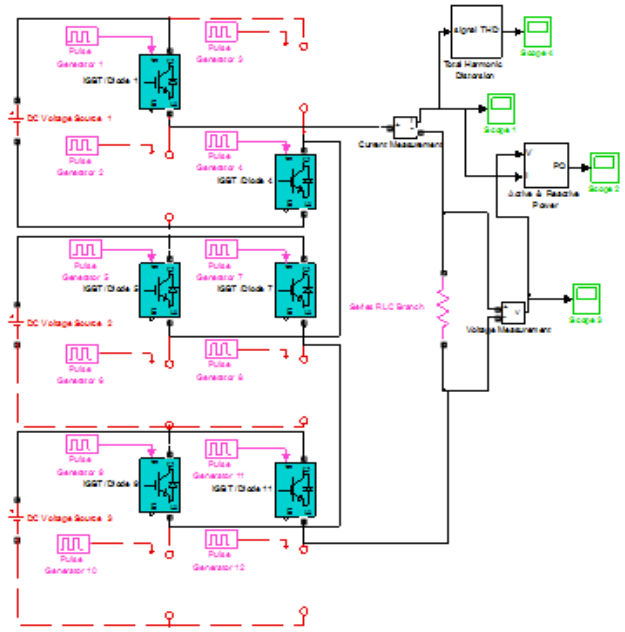
Figure 3: Single phase seven level cascaded H-bridge inverter.

A. MODE OF OPERATION

The following are the mode of operation involve in seven-level CHB multilevel inverter in one full cycle:
Mode 1:

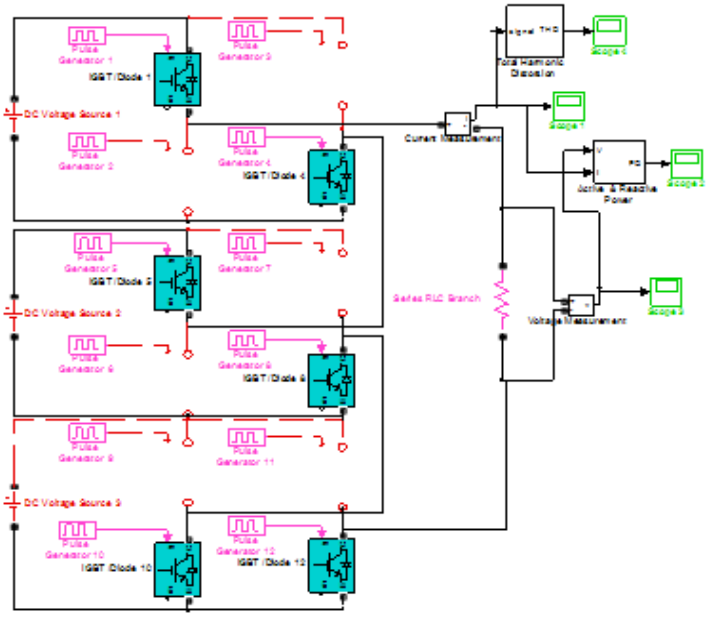


When switches S1, S3, S5, S7, S9 and S11 are turned on, the output voltage obtain will be zero or no source voltage is connected to the load.
Mode 2:



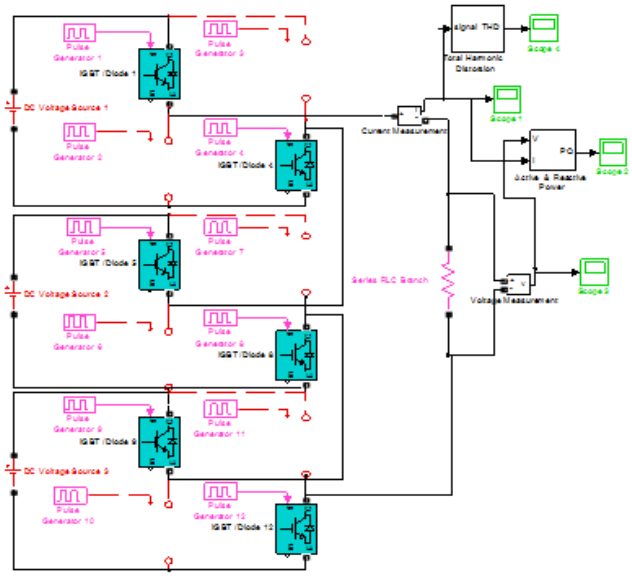
When switches S1, S4, S5, S7, S9 and S11 are turned on, the source voltage connected to the load will be +Vdc1 (i.e. output voltage will +V).

Mode 3:



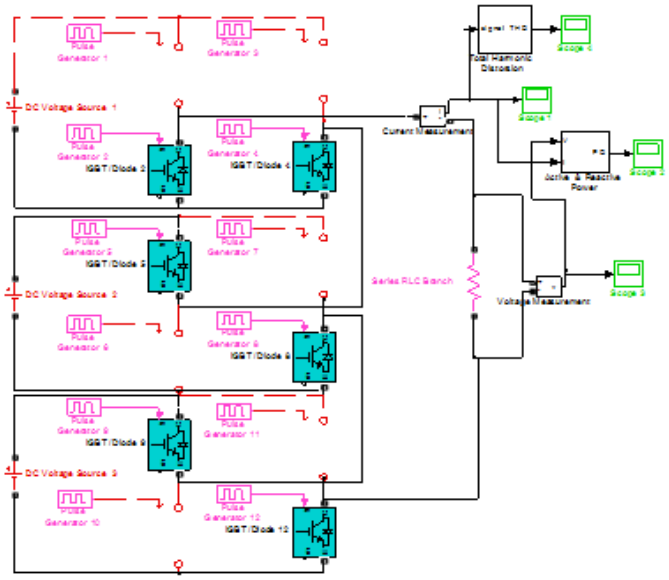
When switches S1, S4, S5, S8, S10 and S12 are turned on, the output voltage across the load will be Vdc1 + Vdc2= +2V.

Mode 4:



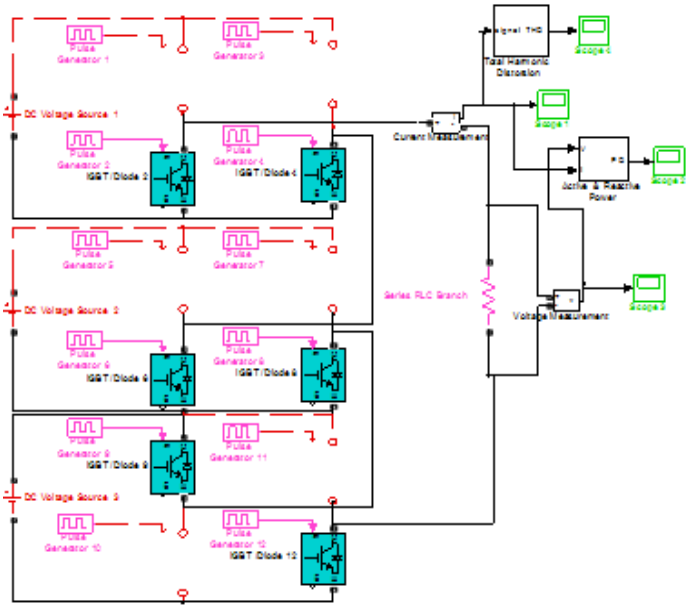
When switches when switches S1, S4, S5, S8, S9 and S12 are turned on, the output voltage will be Vdc1 + Vdc2 + Vdc3 = 3V.

Mode 5:



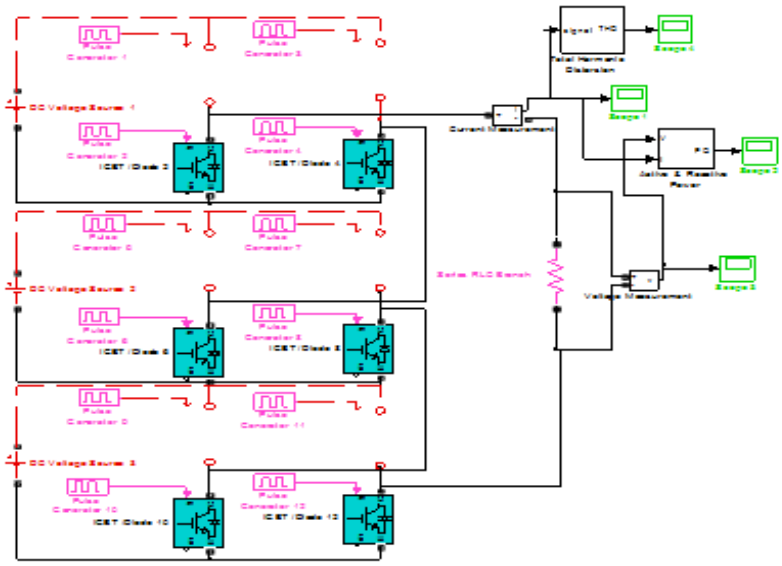
When switches S2, S4, S5, S8, S9 and S12 are turned on, the voltage across the load will be Vdc2 + Vdc3= +2V. (i.e. the output voltage is 2V).

Mode 6:



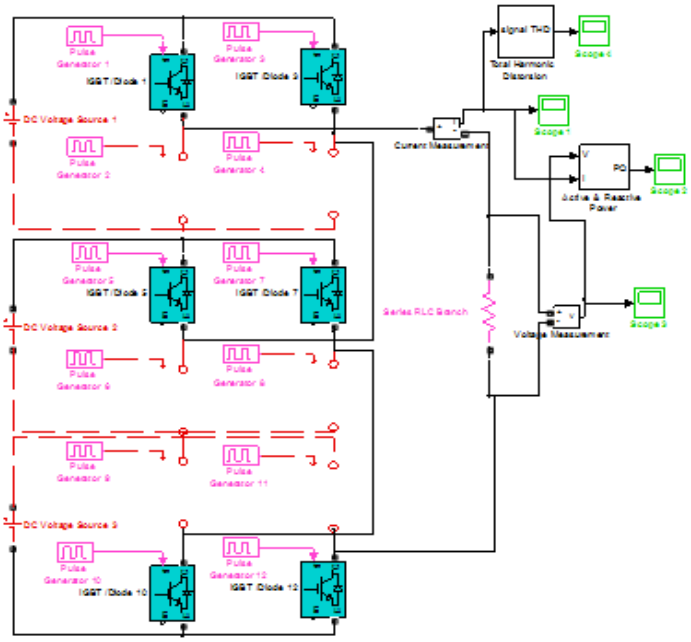
When switches S2, S4, S6, S8, S9 and S12 are turned on, the voltage across the load will be Vdc3 (i.e. output voltage is +V).

Mode 7:



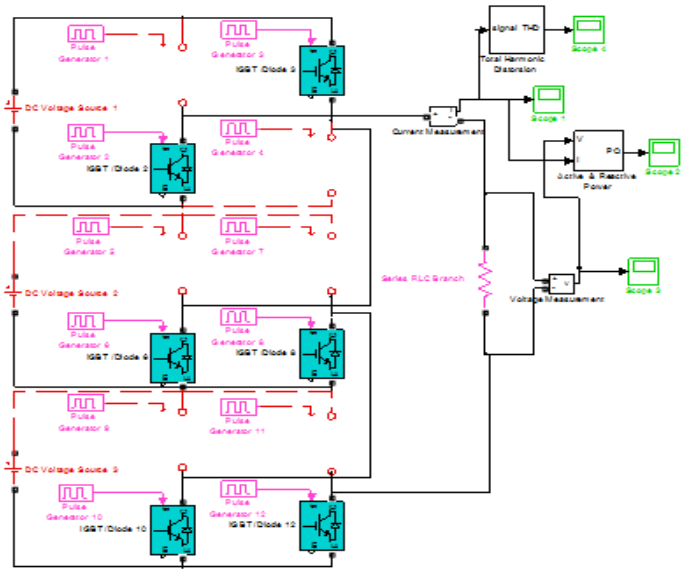
When switches S2, S4, S6, S8, S10 and S12 are turned on, the voltage across the load will be zero.

Mode 8:



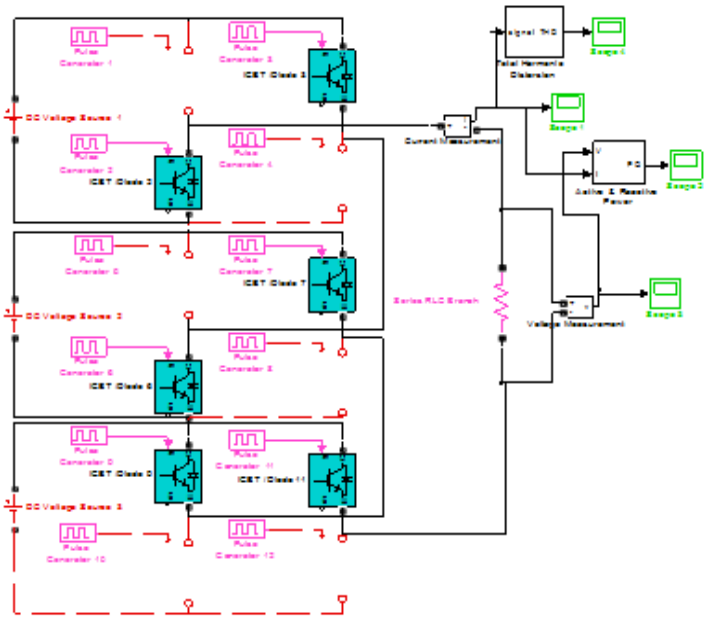
When switches S1, S3, S5, S7, S10 and S12 are turned on, the voltage across the load will be zero.

Mode 9:



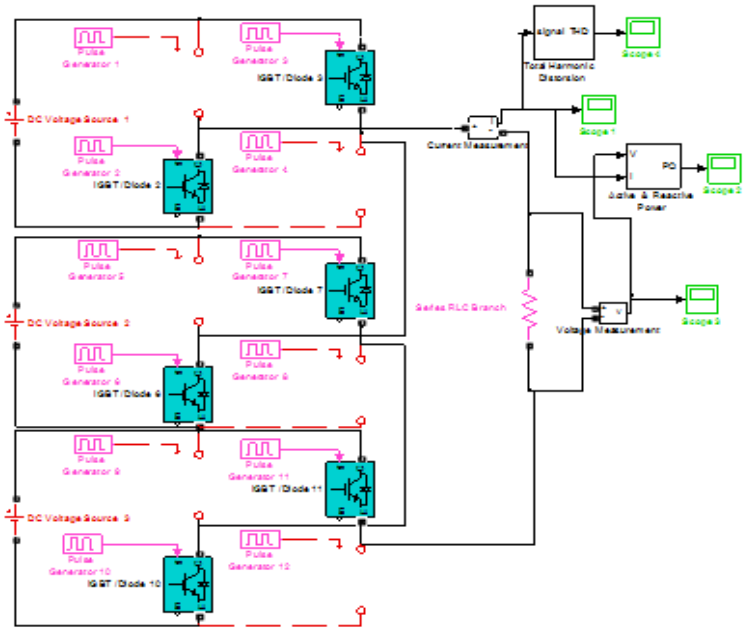
When switches S2, S3, S6, S8, S10 and S12 are turned on, the voltage across the load will be negative voltage (-Vdc1).

Mode 10:



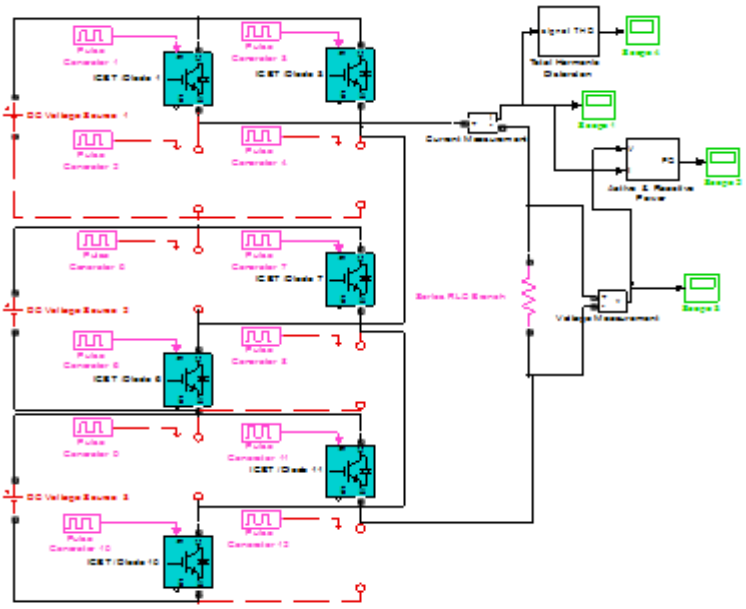
When switches S2, S3, S6, S7, S9 and S11 are turned on, the voltage across the load will be (-Vdc1 -Vdc2 = -2V).

Mode 11:



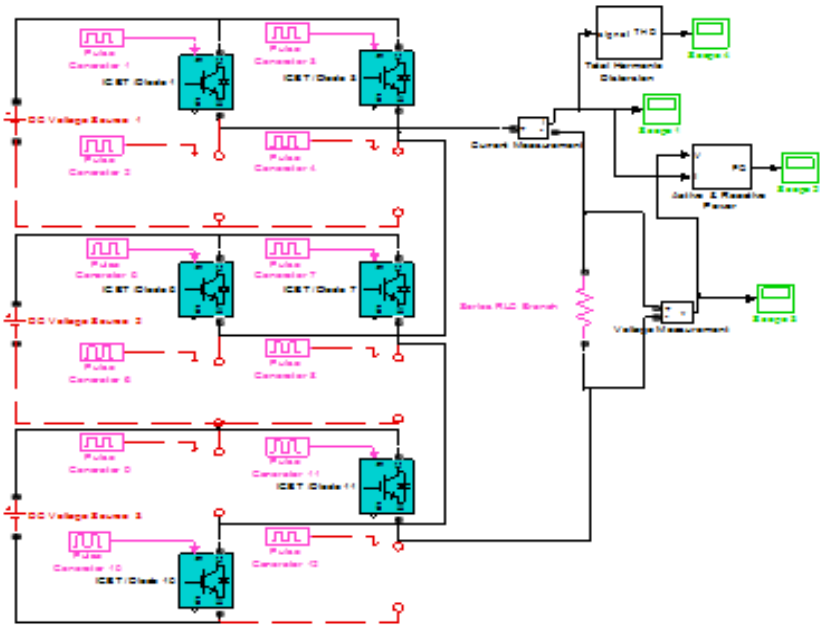
When switches S2, S3, S6, S7, S10 and S11 are turned on, the voltage across the load will be (-Vdc1 -Vdc2 -Vdc3 = -3V).

Mode 12:



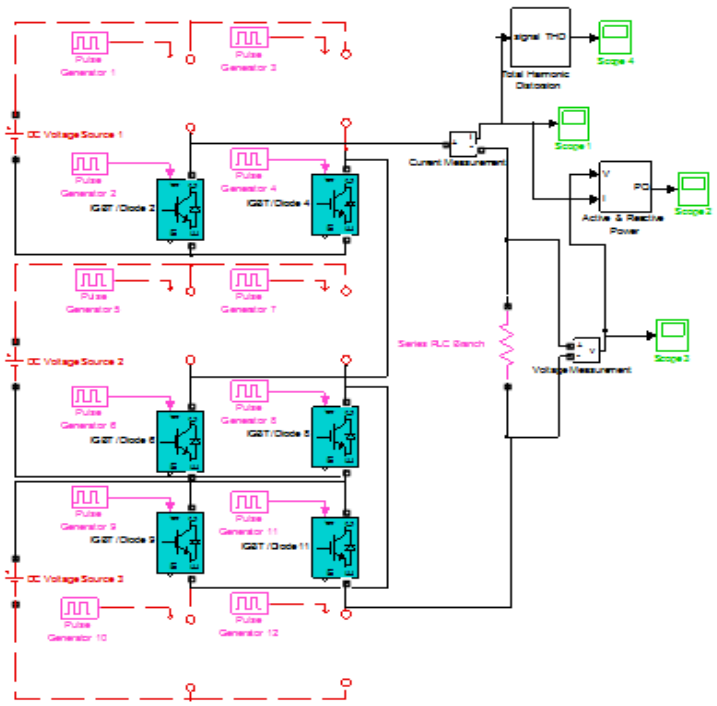
When switches S1, S3, S6, S7, S10 and S11 are turned on, the voltage across the load will be (-Vdc2 -Vdc3 = -2V).

Mode 13:



When switches S1, S3, S5, S7, S10 and S11 are turned on, the voltage across the load will be (-Vdc3 = -V).

Mode 14:



When switches S2, S4, S6, S8, S9 and S11 are turned on, the voltage across the load will be zero.

Table 5: Mode of operation involved in a single phase seven levels Cascaded H-Bridge inverter.

Mode	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	Vdc1	Vdc2	Vdc3	Output voltage
1	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0	0
2	1	0	0	1	1	0	1	0	1	0	1	0	1	0	0	+V
3	1	0	0	1	1	0	0	1	0	1	0	1	1	1	0	+2V
4	1	0	0	1	1	0	0	1	1	0	0	1	1	1	1	+3V
5	0	1	0	1	1	0	0	1	1	0	0	1	0	1	1	+2V
6	0	1	0	1	0	1	0	1	1	0	0	1	0	0	1	+V
7	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0
8	1	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0
9	0	1	1	0	0	1	0	1	0	1	0	1	-1	0	0	-V
10	0	1	1	0	0	1	1	0	1	0	1	0	-1	-1	0	-2V
11	0	1	1	0	0	1	1	0	0	1	1	0	-1	-1	-1	-3V
12	1	0	1	0	0	1	1	0	0	1	1	0	0	-1	-1	-2V
13	1	0	1	0	0	1	1	0	1	0	1	0	0	0	-1	-V
14	0	1	0	1	0	1	0	1	1	0	1	0	0	0	0	0

VI. SWITCHING ANGLE OF A SINGLE PHASE SEVEN LEVEL CHB INVERTER:

Switching angle of a single phase seven level Cascaded H-Bridge inverter is calculated using Equal phase (EP) method. The switching angles are distributed averagely in the range between 0 to π. The main switching angles are obtained by this formula;

Switching angle (αi) = i x 180/m (7)

Where i =1, 2, 3……. (m-1) /2 and m is the number of voltage level.

Then other switching angles in second, third, and fourth quadrants of sine wave are derived from the main switching angles.

Substituting equation 2 above for calculation of seven level switching angles, we have:

$\alpha 1$ = 1 x 180/7 = 25.71
$\alpha 2$ = 2 x 180/7 = 51.42
$\alpha 3$ = 3 x 180/7 = 77.14
$\alpha 4$ = 4 x 180/7 = 102.71
$\alpha 5$ = 5 x 180/7 = 128.57
$\alpha 6$ = 6 x 180/7 = 154.29
$\alpha 7$ = 7 x 180/7 = 180
$\alpha 8$ = 8 x 180/7 = 205.71
$\alpha 9$ = 9 x 180/7 = 231.43
$\alpha 10$ = 10 x 180/7 = 257.14
$\alpha 11$ = 11 x 180/7 = 282.86
$\alpha 12$ = 12 x 180/7 = 308.57
$\alpha 13$ = 13 x 180/7 = 334.29
$\alpha 14$ = 14 x 180/7= 360

Table 6: Switching time table for single phase seven level CHB inverter.

Pulse number	0	V	2V	3V	2V	V	0	0	-V	-2V	-3V	-2V	-V	0
Switching angle	25.71	51.42	77.14	102.86	128.57	154.29	180	205.71	231.43	257.14	282.86	308.57	334.29	360
Time (second)	0.0014	0.0028	0.0042	0.0057	0.0071	0.0085	0.0100	0.0114	0.0128	0.0142	0.0157	0.0171	0.0185	0.02
S1 S4 S8 S12				(35.7 %)										
S5				(21.42 %)										
S9				(7.14 %)										
S2 S6 S10 S11											(35.7%)			
S7											(21.42 %)			
S3											(7.14%)			

B. Mathematical Model

Fourier series of the waveform of single phase cascaded multilevel inverter

$f(x) = a_0 + \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t)$(8)

Fourier series

$a_0 = \frac{1}{T}\int_0^T f(t)dt = 0$ (9)

$a_n = \frac{2}{T}\int_0^T f(t)\cos n\omega t dt = 0$ (10)

$b_n = \frac{2}{T}\int_0^T f(t)\sin n\omega t dt = V_n$ (11)

1. For single phase Half-bridge cascaded inverter.

$Vn = \frac{2}{T}\int_0^{\pi}\frac{Vdc}{2}\sin n\omega t dt + \frac{2}{T}\int_{\pi}^{2\pi} -\frac{Vdc}{2}\sin n\omega t dt$ (12)

Note: $period(T) = 2\pi$, $\omega = \frac{2\pi}{T}$ (13)

$Vn = \frac{2}{2\pi}\int_0^{\pi}\frac{Vdc}{2}\sin n\omega t dt + \frac{2}{2\pi}\int_{\pi}^{2\pi} -\frac{Vdc}{2}\sin n\omega t dt$ (14)

$Vn = \frac{2Vdc}{4\pi}[\int_0^{\pi}\sin n\omega t dt - \int_{\pi}^{2\pi}\sin n\omega t dt]$ (15)

$Vn = \frac{Vdc}{2\pi}\left[\frac{1}{n\omega}[-\cos n\omega t]_0^{\pi} - \frac{1}{n\omega}[-\cos n\omega t]_{\pi}^{2\pi}\right]$ (16)

$Vn = \frac{Vdc}{2n\omega\pi}[(-\cos n\omega\pi - (-\cos n\omega 0)) - (-\cos n\omega 2\pi + \cos n\omega\pi)]$ (17)

$Vn = \frac{Vdc}{2n\pi}[1+1+1+1]$

$= \frac{4Vdc}{2n\pi} = \frac{2Vdc}{n\pi}$ (18)

Fundamental voltage $(V_1) = \frac{2Vdc}{\pi}$ (19)

V_1, rms $= \frac{2Vdc}{\sqrt{2}n\pi}$ (20)

$V_0(t) = \sum_{n=1,2..}^{\infty}\frac{4Vdc}{n\pi}\sin n\omega t$ (21)

II. For single phase cascaded multilevel inverter

$Vn = \frac{2}{T}[\int_{\theta}^{\pi-\theta} Vdc\sin n\omega t dt - \int_{\pi+\theta}^{2\pi-\theta} Vdc\sin n\omega t dt]$ (22)

Note : $period(T) = 2\pi$, $\omega = \frac{2\pi}{T}$ (23)

$Vn = \frac{2Vdc}{2\pi}[\int_{\theta}^{\pi-\theta}\sin n\omega t dt - \int_{\pi+\theta}^{2\pi-\theta}\sin n\omega t dt]$ (24)

$Vn = \frac{Vdc}{\pi}\left[\frac{1}{n\omega}[-\cos n\omega t]_{\theta}^{\pi-\theta} - \frac{1}{n\omega}[-\cos n\omega t]_{\pi+\theta}^{2\pi-\theta}\right]$ (25)

$Vn = \frac{Vdc}{n\pi}[(-\cos n(\pi-\theta) + \cos n\theta) - (-\cos n(2\pi-\theta) + \cos n(\pi+\theta)]$ (26)

Note that: $\cos n\theta = -\cos n(\pi-\theta) = \cos n(2\pi-\theta) = -\cos n(\pi+\theta)$ (27)

Therefore,

$Vn = \frac{4Vdc}{n\pi}(\cos n\omega\theta)$

$= \frac{2}{n\pi}\int_{\theta}^{\pi-\theta} Vdc\sin n\omega t dt$ (28)

The Fourier series of the waveform of single phase three-level cascaded MLI is

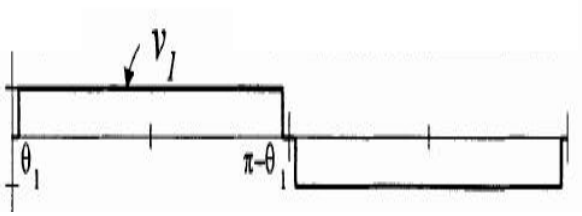


Figure 4: Single – Phase Voltage Output

$V_0(t) = \sum_{n=odd}^{\infty} Vn\sin n\omega t.$ (29)

The fundamental voltage

$(V_1) = \frac{4Vdc}{\pi}\cos\theta$ (30)

$V_1, \text{rms} = \frac{V_1}{\sqrt{2}} = \frac{4Vdc}{\sqrt{2}\pi}$ (31)

The total harmonics distortion

$(\text{THD}) = \sqrt{(\sum_{n=1,2,3\ldots}^{\infty} V_n^2, rms - V_1^2, rms)} \frac{1}{V_1^2, rms}$ (32)

$= \frac{\sqrt{[V_{rms}^2 - V_{1,rms}^2]}}{V_{1,rms}}$ (33)

For resistive load the amplitude current

$(I_n) = \frac{V_n}{R}$ (34)

For RL load amplitude current

$(I_n) = \frac{V_n}{\sqrt{[R^2 + n\omega L^2]}}$ (35)

II. For five-level single phase CHB MLI the Fourier series is

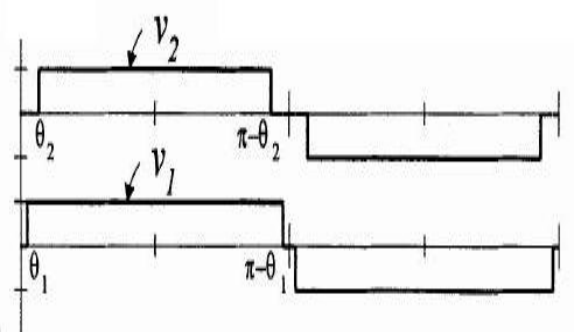


Figure 5: Five-Level Single – Phase Voltage Output

$V_0(t) = \sum_{n=odd}^{\infty} Vn \sin n\omega t.$ (36)

$Vn = \frac{4Vdc}{n\pi}(\cos n\omega\theta_1 + \cos n\omega\theta_2)$ (37)

$V_1 = \frac{4Vdc}{\pi}(\cos\theta_1 + \cos\theta_2)$

= Fundamental voltage (38)

III. For seven-level single phase CHB MLI the Fourier series is

$V_0(t) = \sum_{n=odd}^{\infty} Vn \sin n\omega t.$ (39)

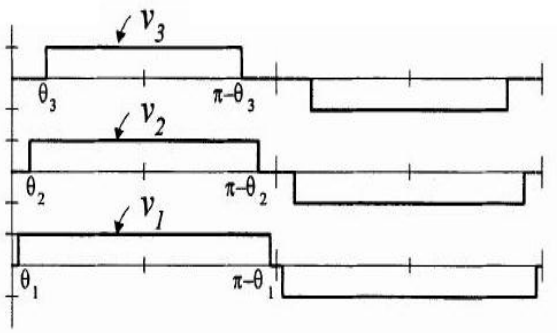


Figure 6: Seven – Level Single – Phase Voltage Output

$V_0(t) = \sum_{n=odd}^{\infty} Vn \sin n\omega t.$ (40)

$V_n = \frac{4Vdc}{n\pi}(\cos n\omega\theta_1 + \cos n\omega\theta_2 + \cos n\omega\theta_3)$ (41)

$V_1 = \frac{4Vdc}{\pi}(\cos\theta_1 + \cos\theta_2 + \cos\theta_3)$

= Fundamental voltage (42)

Modulation index (M_i) is the ratio of the amplitude of the fundamental frequency component of V_0 to the amplitude of fundamental frequency component of a square wave of amplitude 2Vdc which is $2\left(\frac{4Vdc}{\pi}\right)$. modulation index can also be defined as the ratio of maximum voltage value of modulating wave (V_m) to carrier wave voltage (V_{cr}) (i.e. V_m / V_{cr}).

$M_i = (V_1)/2(\frac{4Vdc}{\pi}) = \frac{1}{2}(\cos\theta_1 + \cos\theta_2)$ (43)

IV. For three source voltage (Vdc)

$M_i = (V_1)/3(\frac{4Vdc}{\pi})$

$= \frac{1}{3}(\cos\theta_1 + \cos\theta_2 + \cos\theta_3)$ (44)

D. SIMULATION AND RESULT

Simulation of the proposed project is performed using MATLAB simulation and then comparative analysis of different level is done. Some parameters like voltage levels, modulation scheme and total harmonics distortion (THD) is chosen to analyze the level of the CHB MLI.

I. Simulation of a single phase three-level cascaded H-bridge MLI.

Three-level CHB MLI is modeled and simulated based on theoretical concept given in chapter 3 and the simulation parameters are listed in table 7. Then the figures 8, and 9 **show the load voltage and the total harmonics distortion in voltage** waveform.

Table 7: The Simulation parameters 3 levels CHB MLI

Load voltage frequency	50hertz
DC voltage	100volts
Load power	1KW
Number of switches	4 IGBT/diode
Resistor	10 Ohms
THD %	77.39%

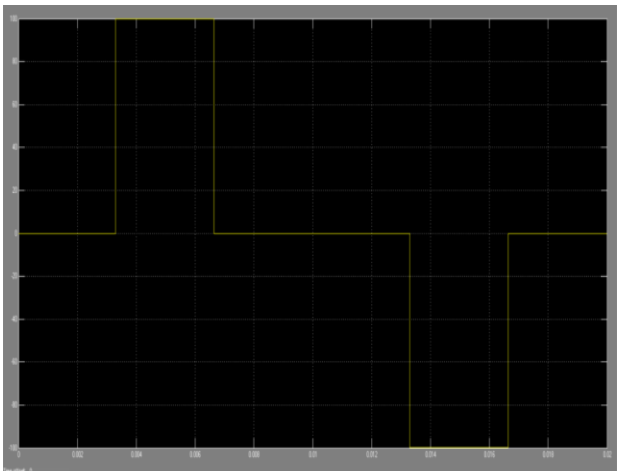


Fig 8: Three-level load voltage

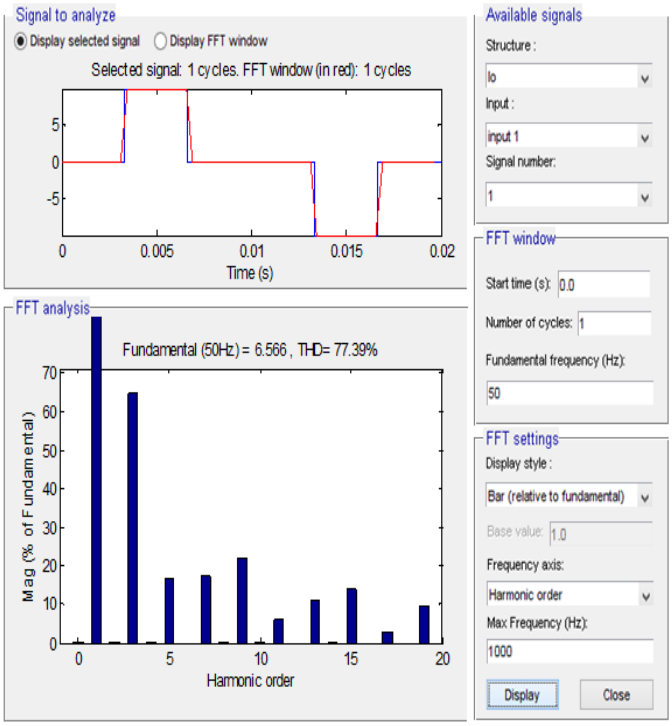


Figure 9: Three-level load voltage and Harmonic analysis of load voltage.

II. Simulation of a Single-Phase Five-Level Cascaded H-Bridge MLI.

Five-level CHB MLI is designed and simulated based on theoretical concept given in chapter 3 very similar to three-level and the simulation parameters are listed in table 8. Then the figures 11, 12 and 13 show the load voltage and the total harmonics distortion in voltage waveform.

Table 8: The simulation parameters for 5 levels CHB MLI

Load voltage frequency	50hertz
DC voltage	200volts
Load power	4KW
Number of switches	8 IGBT/diode
Resistor	10 Ohms
THD %	41.64%

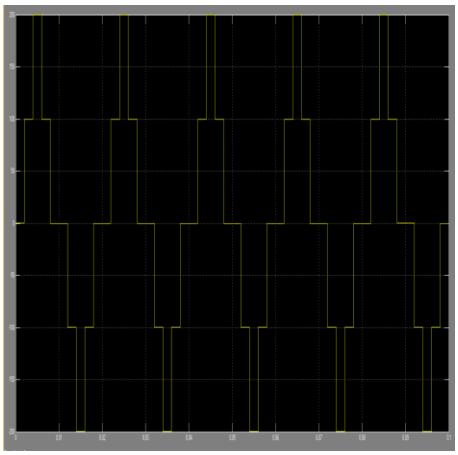


Figure 10: Five-level load voltage (5cycle)

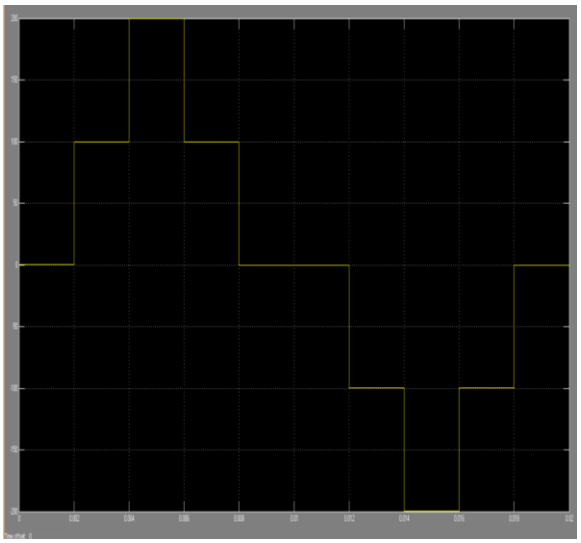


Figure 11: Five-level load voltage.

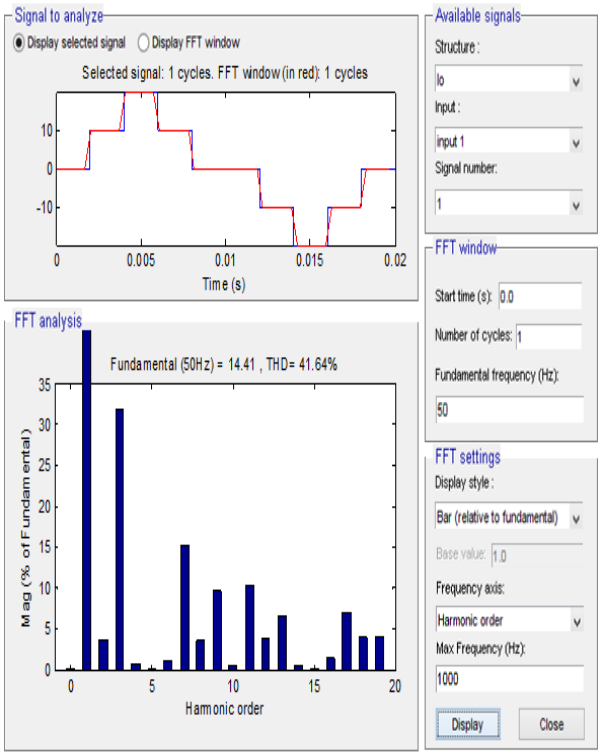


Figure 12: Harmonic analysis of load voltage.

III. Simulation of a single phase Seven-level cascaded H-bridge MLI.

Seven-level CHB MLI is designed and simulated based on theoretical concept given in chapter 3 very similar to three-level and the simulation parameters are listed in table 9. Then the figures 14, 15 and 16 show the load voltage and the total harmonics distortion in voltage waveform.

Table 9: The Simulation parameters for 7 levels CHB MLI

Load voltage frequency	50hertz
DC voltage	300volts
Load power	9KW
Number of switches	12 IGBT/diode
Resistor	10 Ohms
THD %	25.08%

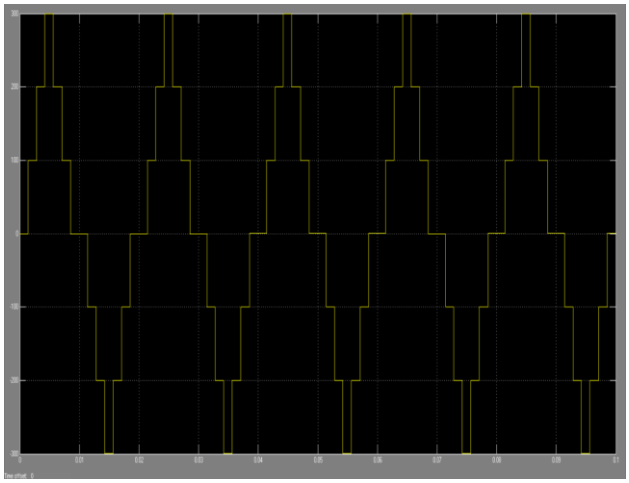


Fig 13: Seven-level load voltage (5cycle)

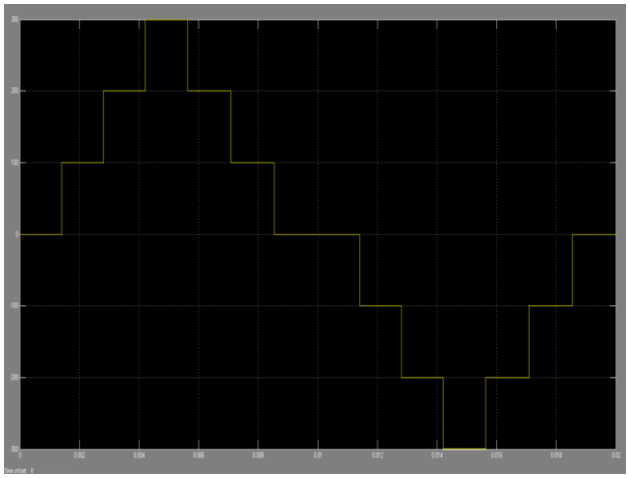


Fig 14: Seven-level load voltage (1cycle).

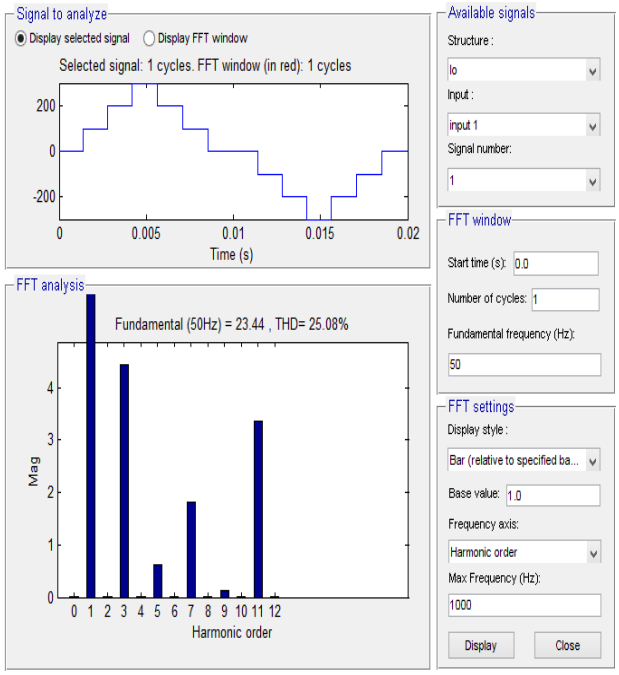


Fig 15: Harmonic analysis of load voltage.

IV. The comparative and comprehensive result of single-phase Cascaded H-Bridge MLI.

Table 10: The comparative result of single-phase Cascaded H-Bridge MLI.

Simulation parameters	3-level	5-level	7-level
Load voltage frequency	50hertz	50hertz	50hertz
DC voltage	100volts	200volts	300volts
Load power	1KW	4KW	9KW
Number of switches	4 IGBT/diode	8 IGBT/diode	12 IGBT/diode
Resistor	10 Ohms	10 Ohms	10 Ohms
THD %	77.39%	41.64%	25.08%

Table 11: Simulation result of one full bridge three level MLI with ten different capacities of source DC Voltages.

Serial No;	Input DC Voltage(V)	No of IGBT Switches	Output DC Voltage(V)	Output Load(Ω)	Load Power (KW)	THD%
1	100	4	100	10	1	77.39
2	200	4	200	10	4	77.39
3	300	4	300	10	9	77.39
4	400	4	400	10	16	77.39
5	500	4	500	10	25	77.39
6	600	4	600	10	36	77.39
7	700	4	700	10	49	77.39
8	800	4	800	10	64	77.39
9	900	4	900	10	81	77.39
10	1000	4	1000	10	100	77.39

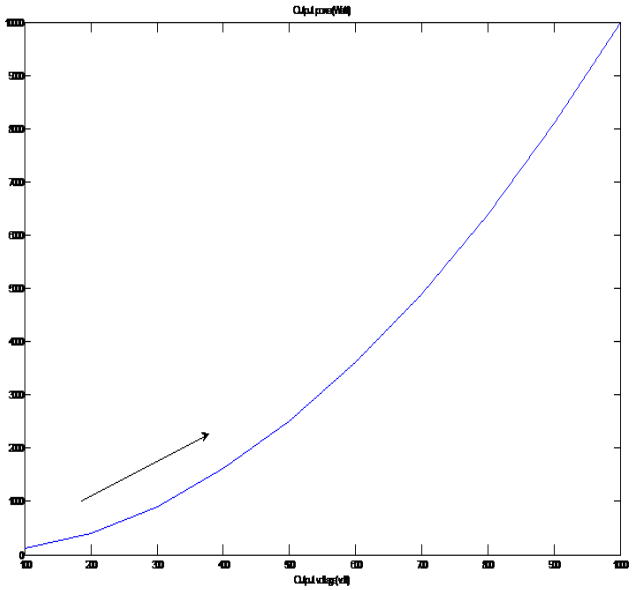


Fig 16: Graph of output voltage against load power from Table 11

Table 12: Simulation result of two full bridge single phase five level MLI with equal capacity of source DC voltages

Serial No	Input DC Voltage(V)	No of IGBT switches	Output DC Voltage(V)	Output load(Ω)	Load Power (KW)	THD%
1	50+50	8	100	10	1	41.64
2	100+100	8	200	10	4	41.64
3	150+150	8	300	10	9	41.64
4	200+200	8	400	10	16	41.64
5	250+250	8	500	10	25	41.64
6	300+300	8	600	10	36	41.64
7	350+350	8	700	10	49	41.64
8	400+400	8	800	10	64	41.64
9	450+450	8	900	10	81	41.64
10	500+500	8	1000	10	100	41.64

Table 13: Simulation Result of two Full Bridge Single phase five level MLI with Unequal Capacity of Source DC Voltages.

Serial No;	Input DC Voltage(V)	No of IGBT Switches	Output DC Voltage(V)	Output Load(Ω)	Load Power (KW)	THD%
1	60+40	8	100	10	1	42.74
2	150+50	8	200	10	4	48.10
3	200+100	8	300	10	9	44.63
4	250+150	8	400	10	16	43.35
5	300+200	8	500	10	25	42.74
6	350+250	8	600	10	36	43.24
7	400+300	8	700	10	49	42.20
8	450+350	8	800	10	64	42.07
9	500+400	8	900	10	81	41.98
10	550+450	8	1000	10	100	41.92

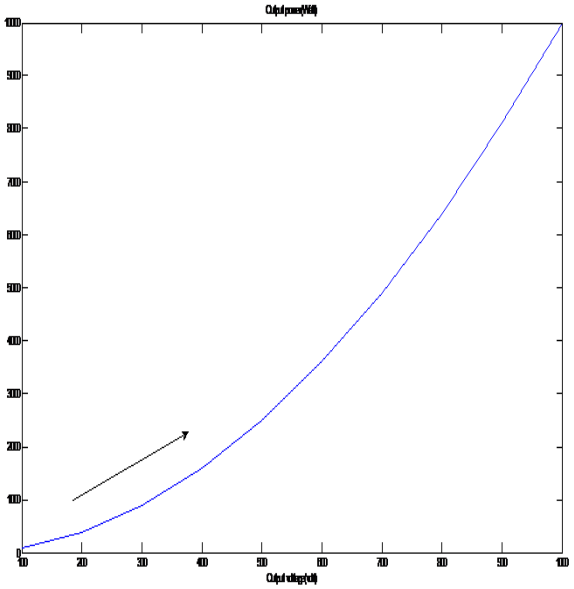


Fig 17: Graph of output voltage against load power from Table 12 and 13

Table 14: Simulation result of three full bridge single phase seven level MLI with equal capacity of source DC voltages

Serial No	Input DC Voltage(V)	No of IGBT Switches	Output DC Voltage(V)	Output Load(Ω)	Load Power (KW)	THD%
1	50+50+50	12	150	10	2.25	25.08
2	100+100+100	12	300	10	9.00	25.08
3	150+150+150	12	450	10	20.25	25.08
4	200+200+200	12	600	10	36.00	25.08
5	250+250+250	12	750	10	56.25	25.08
6	300+300+300	12	900	10	81.00	25.08
7	350+350+350	12	1050	10	110.25	25.08
8	400+400+400	12	1200	10	144.00	25.08
9	450+450+450	12	1350	10	182.25	25.08
10	500+500+500	12	1500	10	225.00	25.08

Table 15: Simulation result of three full bridge single phase seven level MLI with unequal capacity of source DC voltages

Serial No	Input DC Voltage(V)	No of IGBT Switches	Output DC Voltage(V)	Output Load(Ω)	Load Power (KW)	THD%
1	55+50+45	12	150	10	2.25	25.26
2	150+100+50	12	300	10	9.00	29.06
3	200+150+100	12	450	10	20.25	26.92
4	250+200+150	12	600	10	36.00	26.13
5	300+250+200	12	750	10	56.25	25.76
6	350+300+250	12	900	10	81.00	25.56
7	400+350+300	12	1050	10	110.25	25.43
8	450+400+350	12	1200	10	144.00	25.35
9	500+450+400	12	1350	10	182.25	25.30
10	550+500+450	12	1500	10	225.00	25.26

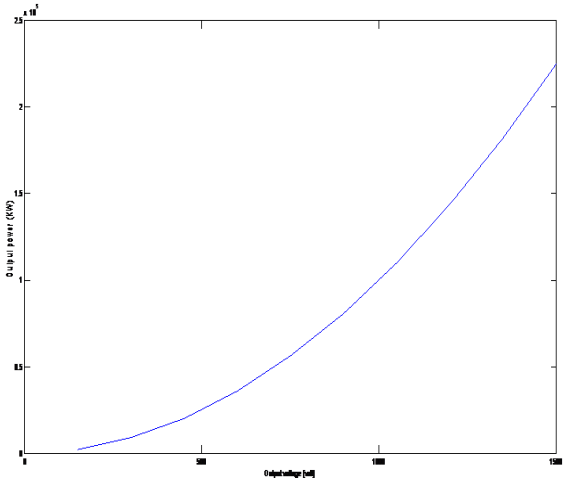


Figure 18: Graph of output voltage against load power from Table 14 and 15

CONCLUSION

In conclusion, the single phases three, five and seven-level cascaded H-bridge multilevel inverter topologies have been studied and simulated. It is observed that the more we add more cells (i.e. a single H-bridge inverter), the more the output step voltage increases in level. Then the comparison between these levels stated above shows that as the number of output voltage level increases, the required component increases and thereby increases the cost, the total harmonics distortion (THD) decreases and it keep moving towards pure sine wave. This study reveals that:

1. The input voltage for the various H-bridges in multilevel inverters should be kept equal to keep the THD as low as possible.
2. The A.C output voltage of multilevel inverters increases with increased input D.C voltage.
3. The general objective of keeping the harmonic content low is served by increase the number of levels.
4. Harmonic increase results with unbalance input D.C voltage across different H-bridge of the inverter.

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