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Harmonic Reduction of Cascaded H-Bridge Multilevel Inverter Based on Newton-Raphson

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Abstract

Multilevel inverter using cascaded H-bridge inverter with separated dc source (SDCSs) are introduced in single phase structure. The output voltage is the sum of the output of each H-bridge cell. The output voltage waveform is ideal with suitable switching angle estimation to produce required fundamental voltage. This paper presents the simulation of 5-level cascaded H-bridge multilevel inverter with selecting different switching angle based on Newton-Raphson method is used for angle optimization. Simulation work is done by using MATLAB/Simulink software.

Keywords— Cascaded multilevel, switching angle, output voltage, MATLAB/Simulink, and total harmonic distortion (THD)

I. Introduction

Inverter is circuit that convert power from a direct current (DC) source to an alternative current (AC) load. Multilevel inverter is the new types of inverter that device which can produce different voltage levels. Over the past decade, the multilevel inverter has its own interests in the world of power electronic technology. These types of inverter has been plays the important role as well as industry in the recent decade for high power and medium voltage energy for control application. This is due to their capability to synthesize switched waveform with lower levels of harmonic distortion than an equivalently rated two levelinverter.

The multilevel inverter concept is used to decrease the harmonic distortion[1] in the output waveform without decreasing the inverter power output. It has several advantages such as lower switching frequency and switching losses, lower voltage device evaluation, lower harmonic distortion, high power quality waveform, higher efficiency, reduction of electromagnetic interference (EMI) and interfacing renewable energy sources such as photovoltaic to the electric power grid[2].

Nowadays, three common topologies of multilevel inverter have been proposed, the three topologies are diode-clamped, flying capacitors (FCs) and cascaded H-bridge (CHB)[3]. Type of multilevel inverter which using a single dc source rather than multiple sources is the diode-clamped multilevel inverter. While, flying capacitor type is designed by series connection of capacitor clamped switching cells. Cascaded H-bridge type which able to be series or parallel connected and also consists of a series of H-bridge cells to synthesize a required voltage from several separate DC sources which recoverable from batteries, fuel cells, renewable energy or ultra-capacitor[4]. This CHB topology has the least components for a given number of levels[5]. Thus, CHB is more advantageous among others multilevel inverter topologies.

An appropriate switching angles have to be generated using optimizing techniques to control switching frequencies of each semiconductors switches connected. The pure sinusoidal voltage waveform can be obtained by increasing the number of DC sources. Thus, insulator gate bipolar transistor (IGBT) is an example of semiconductors switches that are switched on and off in any ways to keep the total harmonic distortion (THD) percentage to its minimum value. These switches also have low block voltage and high switching frequency.

This paper focuses on comparison between optimize and non-optimize the voltage output waveform of a single phase 5-level cascaded H-bridge multilevel inverter. Switching angles are calculated by the help of optimization technique. The conventional Newton-Raphson is the optimization method that able to solve the transcendental equation to eliminatethe particular harmonics. This is because the harmonic equation obtained is nonlinear.

II. 5-LEVEL CASCADED H-BRIDGE MLI TOPOLOGY

Various MLI topologies have been introduced and discussed through established journals. CHB MLI topology is the most efficient device with respect to the number of output voltage levels. In this paper, five level cascaded H-bridge MLI configuration is implemented.

A single phase H-bridge inverter is connected to each separate dc source and this will generate three different voltage outputs, +Vdc, 0, and –Vdc. To synthesize a multilevel waveform, the ac output of each of the different H-bridge cells is connected in series. The number of phase voltage levels at the inverter terminal is 2U+1, where U is the number of dc link voltages[6]. A five-level output phase voltage waveform can be obtained with two separated dc sources and two H-bridge cells. Fig. 1 shows a general single phase 5-level cascaded inverter. It has eight main switches in H-bridge configuration, S1, S2, S3, S4, S5, S6, S6, S7 and S8. All switches operate with a switching scheme like amplitude or harmonic control[7]. Each H-bridge operates at different delay angle θ.

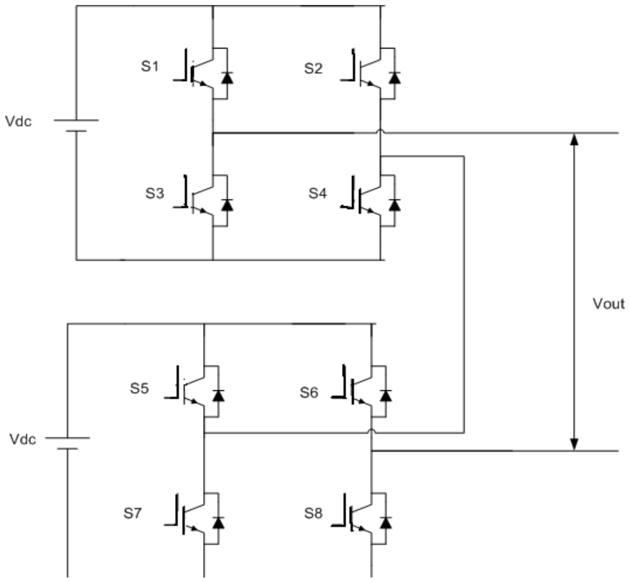

Fig. 1. Cascaded H-bridge Five Level Multilevel Inverter

The total instantaneous voltage on the output of five-level multilevel inverter can generate five different the output of each of the H bridges is 2Vdc, Vdc, 0, -Vdc, -2Vdc,as was illustrated in Fig 2.

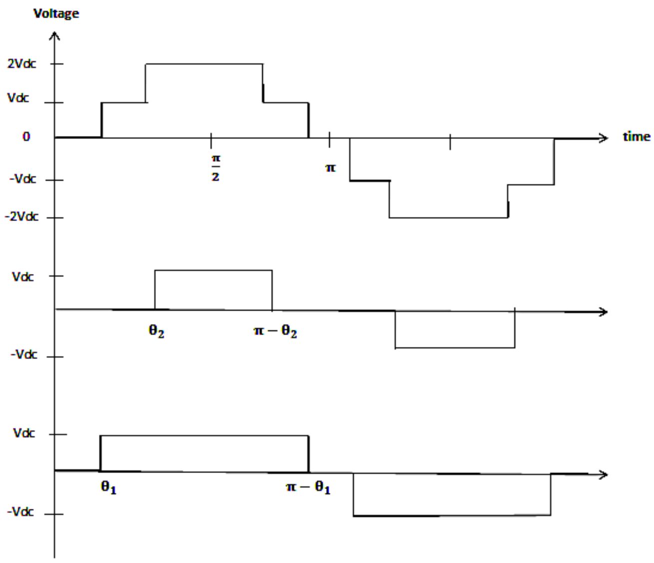

Fig. 2. 5-level cascaded H-bridge MLI of Output Voltage Waveform

The Fourier series for the total output voltage as equation (1). Two sources circuits contains only odd-numbered harmonic and is

$$V_o = \frac{4V_{dc}}{\pi}\sum_{n=1,3,5,7,9\ldots}^{\infty}[\cos(N\theta_1) + \cos(N\theta_2)]\frac{\sin(n\omega_o t)}{n} \quad (1)$$

The modulation index $m_i$is the ratio of the amplitude of the fundamental frequency component of V_o to the amplitude of the fundamental frequency component of a square wave of amplitude $2V_{dc}$, which is $2(\frac{4V_{dc}}{\pi})$. The expression equation of m_i is

$$m_i = \frac{V_1}{2(4V_{dc}/\pi)} \quad (2)$$

For the two separate dc sources inverter, harmonic N can be eliminated by using delay angles as

$$\cos(N\theta_1) + \cos(N\theta_2) = 0 \quad (3)$$

The additional equation derived from (1) for simultaneous solution is required to eliminate Nth harmonic and meet a specified modulation index, then

$$\cos(\theta_1) + \cos(\theta_2) = 2m_i \quad (4)$$

These harmonic equations (3) and (4) are transcendental equations. To solve these simultaneous equations requires an iterative numerical method. Thus, Newton Raphson technique is one of other methods that will be employed for solving these equations.

III. MATHEMATICAL TECHNIQUE OF SWITCHING

In this paper, the values of the conducting angles $\theta_1$and θ_2 can be chosen by solving the transcendental equations using a modulation index of 0.84. Other angles which areθ_3 until $\theta_8$can be obtained by referring the output waveform of 5 levels CHB MLI theory in Fig 2. The different values of $\theta_1$and θ_2 will be comparing between non-optimization and the optimization output waveform of 5 level cascaded H-bridge MLI as the modulation index will remainthe same.

A. Angle Control Calculation

The procedure of detecting attributes and configuration of a system is called optimization[8]. For 5-level inverter, only one harmonic can be eliminated and here, the3rd harmonics is chosen to be removed. Thus, the switching angle can be found by solving transcendental equations by using Newton Raphson technique. These harmonic equations areexpressedas

$$\cos(\theta_1) + \cos(\theta_2) = 2(0.84) \quad (5)$$

$$\cos(3\theta_1) + \cos(3\theta_2) = 0 \quad (6)$$

By using the following trigonometric identities:

$$\cos(3\theta) = 4\cos^3(\theta) - 3\cos(\theta) \quad (7)$$

Equations (5), (6), and (7) are changed into polynomials harmonic equations.

Let the variables,

$$x_1 = \cos(\theta_1) \quad (8)$$

$$x_2 = \cos(\theta_2) \quad (9)$$

Substitute (8) and (9) into (5) and (6) and get these equations,

$$x_1 + x_2 = 2(0.84) \quad (10)$$

$$(4x_1^3 - 3x_1) + (4x_2^3 - 3x_2) = 0 \quad (11)$$

By solving (10) and (11), the function equation obtained is

$$f(x) = 20.05x_2^2 - 33.51x_2 + 13.65 \quad (12)$$

By referring to the iterative method, 6 iteration calculations have been used. The calculated value ofx_2 is 0.7041 while the value x_1 is 0.967. Therefore, the values of switching angle for $\theta_1$and θ_2 are14.73° and 45.23°respectively. Then, the angle values $\theta_3$until $\theta_8$can be obtainedby substituting the values angle $\theta_1$and θ_2 into these equations

$$\theta_3 = \pi - \theta_2 \quad (13)$$

$$\theta_4 = \pi - \theta_1 \quad (14)$$

$$\theta_5 = 2\pi - \theta_4 \quad (15)$$

$$\theta_6 = 2\pi - \theta_3 \quad (16)$$

$$\theta_7 = 2\pi - \theta_2 \quad (17)$$

$$\theta_8 = 2\pi - \theta_1 \quad (18)$$

The solutions of the above equations are shown below

$\Theta_3 = 134.77^{\circ}$, $\theta_4 = 165.27^{\circ}$, $\theta_5 = 194.73^{\circ}$, $\theta_6 = 225.23^{\circ}$

$\theta_7 = 314.77^{\circ}$, $\theta_8 = 345.27^{\circ}$

B. ***Different Switching Angle***

The inverter output is symmetrically switched during the positive half cycle of the fundamental voltage to $+V_{dc}$ at 14.73° and $+2V_{dc}$ at 45.23°, and similarly in the negative half cycle to $-V_{dc}$ at 225.23° and $-2V_{dc}$ at314.77°. Optimization waveform of voltage output which ideal is illustrated as Fig 3.

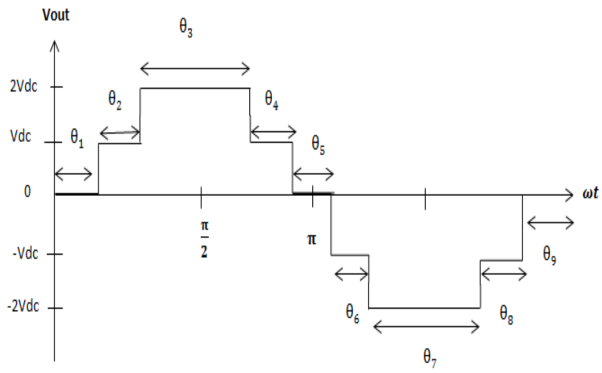

Fig. 3. Optimization of Voltage Output Waveform

If the angle switching is changed with another angles at the same modulation index, the switching scheme of the inverter can be changed too and this will affect the output voltage waveform are not optimize, as was illustrated in Fig 4.

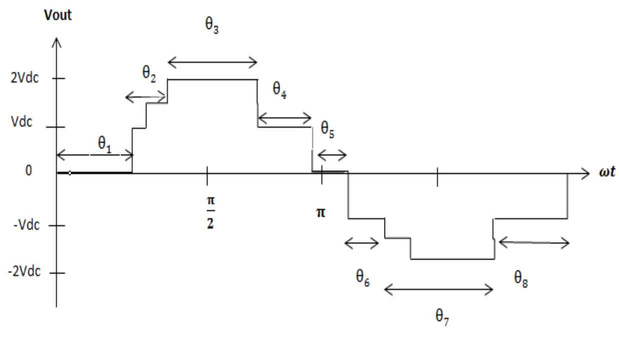

Fig.4. Non-Optimization of Voltage Output Waveform

The switching pattern order of the switches is S1, S2, S3, S4, S5, S6, S7, and S8 is shown in Table 1. The pattern is not fixed as long as the switches are turned on and off in the right sequence as to produce desired output waveform.Switching pattern which is also known as pattern swapping shown in Fig. 2 is used in the five-level cascaded H-bridge multilevel inverter. In this pattern, the first source generate more time in the first half-cycle while the second source generate a longer time in the second half-cycle. Therefore, over one complete period, the sources conduct equally and average power from each source is the same.

Table 1 Switching Pattern for Five-Level Inverter

Voltage Output (V_0)	S1	S2	S3	S4	S5	S6	S7	S8
$V_0 = 2V_{dc}$	1	0	0	1	1	0	0	1
$V_0 = V_{dc}$	1	0	0	0	1	1	0	0
$V_0 = 0$	0	0	0	0	0	0	0	0
$V_0 = -V_{dc}$	0	0	1	1	0	1	1	0
$V_0 = -2V_{dc}$	0	1	1	0	0	1	1	0

IV. SIMULINK MODELS AND RESULTS

Simulation of one phase five-level cascaded H-bridge multilevel is done using MATLAB/SIMULINK software. For simulation of five-level MLI, two dc sources are used as shown in Fig 5. In this simulation model, two 150V dc sources are selected. Pulse generator block is used to conduct the switching pattern and results of pulse generating will control the inverter. The voltage output of the five-level MLI is 300 volts with frequency 50Hz.

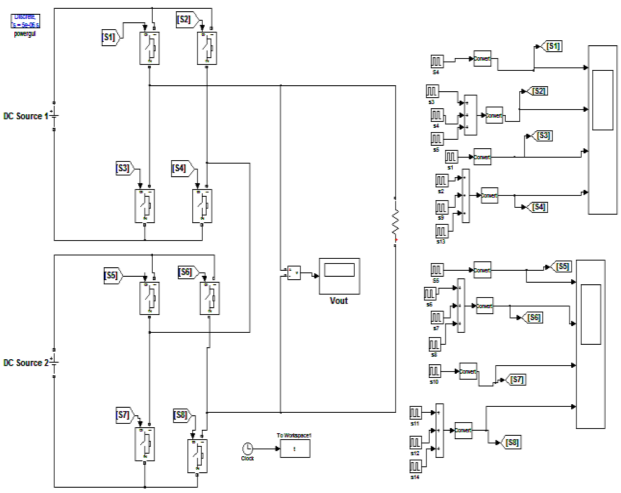

Fig. 5. Five-Level Cascaded H-Bridge MLI Model

A. *Optimization Five-Level CHB MLI*

In this simulation, 0.02 is taken as one period and phase delay is 0.00084 which is switching angle 1 for the positive half cycle whenoutput ofS1 and S2 are in operation at+V_{dc}. For the positive cycle output of S5 and S6 are in operation at+2 $V_{dc}$and phase delay is taken as 0.002505 which is for switching angle 2. Similarly for the negative half cycle at $-V_{dc}$ of output S3 and S4 are in operation while for the negative cycle at $-2V_{dc}$ output of S7 and S8 are in operation. The switching patterns of optimization are shown in Fig. 6 and Fig. 7.

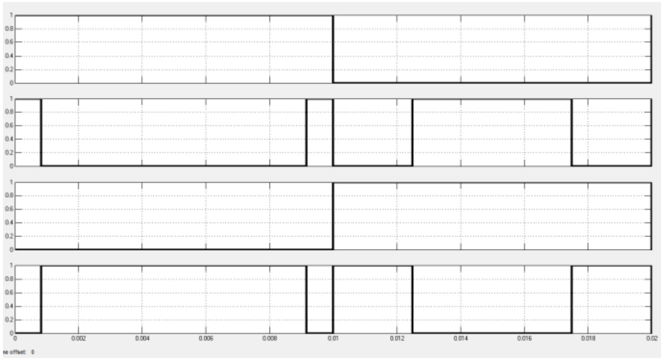

Fig. 6. S1, S2, S3, and S4 Output Waveform (Optimization)

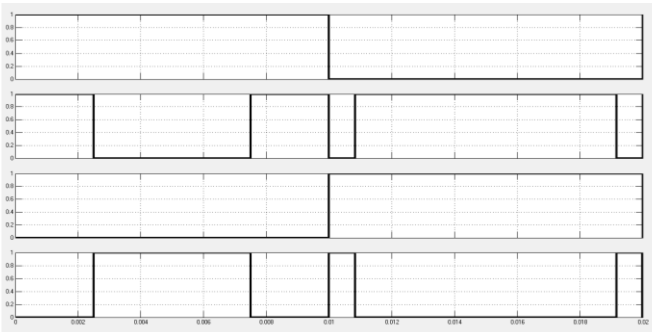

Fig. 7. S5, S6, S7, and S8 Output Waveform (Optimization)

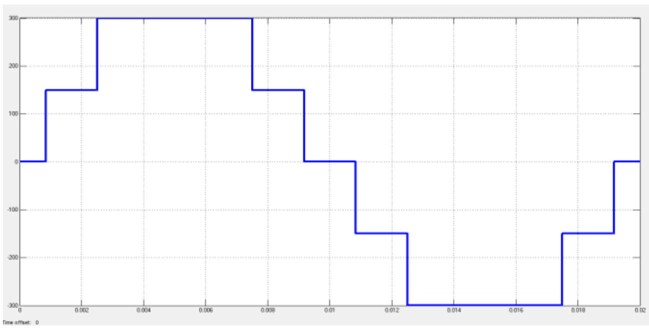

Fig. 8. Voltage Output of 5- Level MLI (Optimization)

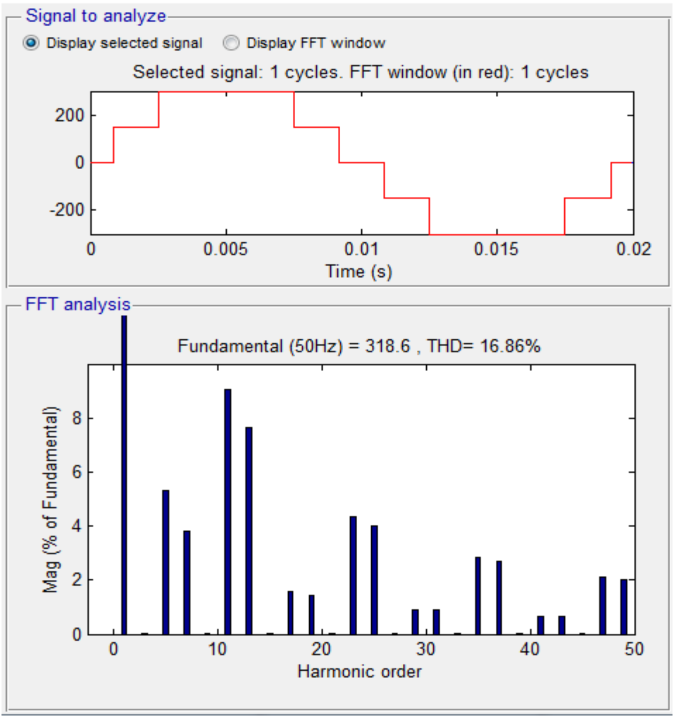

Fig. 9. FFT Analysis (Optimization)

B. ***Non-Optimization Five-Level CHB MLI***

By using the same simulation, the phase delay was changed with 0.00053 which is switching angle 1 for the positive half cycle when output of S1 and S2 are in operation at $+V_{dc}$. For the positive cycle output of S5 and S6 are in operation at $+2\,V_{dc}$ and phase delay was changed to 0.002505 which is switching angle 2. Similarly for the negative half cycle at $-V_{dc}$ of output of S3 and S4 are in operation while for the negative cycle at $-2V_{dc}$ output of S7 and S8 are in operation. The switching patterns of non - optimization are shown in Fig. 10 and Fig. 11.

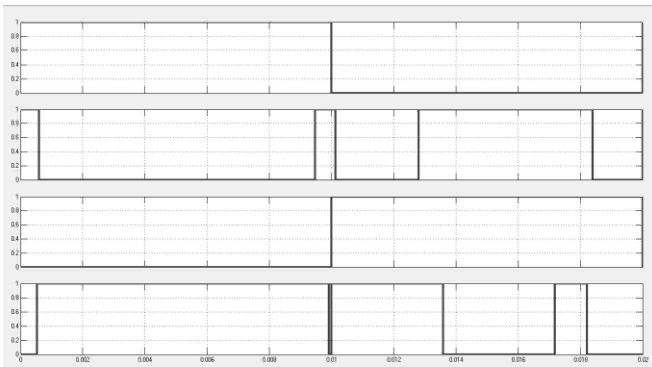

Fig. 10. S1, S2, S3, and S4 Output Waveform (Non-Optimization)

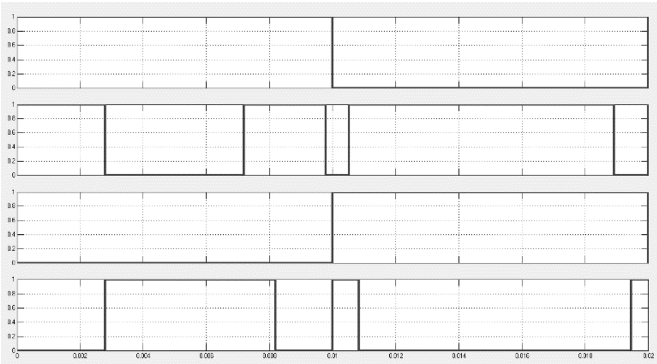

Fig. 11. S5, S6, S7, and S8 Output Waveform (Non-Optimization)

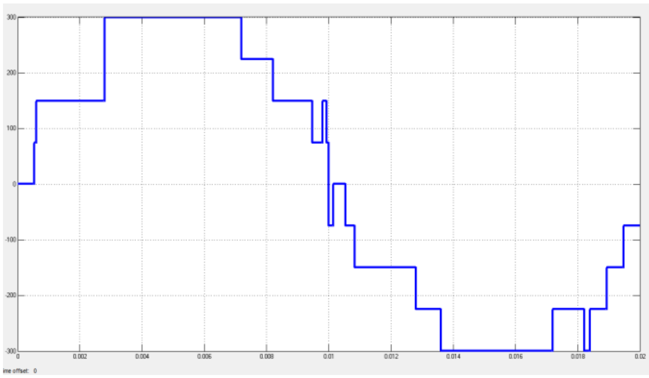

Fig. 12. Voltage Output of 5- Level MLI (Non-Optimization)

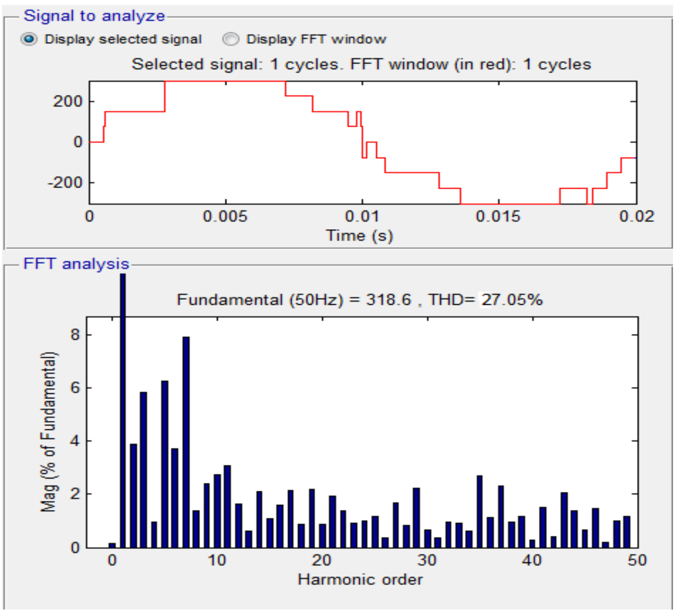

Fig. 13. FFT Analysis (Non- Optimization)

Fig 9 and Fig 13show FFT analysis of line voltage at 0.84 modulation index, while comparisons between optimization and non-optimization have been tabulated at Table 2.

Table 2: Comparison between optimization and non-optimization

	Optimization	Non-Optimization
THD (%)	16.86	27.05
Output Voltage waveform	Is very smooth	Is less smooth

V. CONCLUSIONS

A cascaded H-bridge 5-level multilevel inverter with optimization and non –optimization have been discussed. The simulation results for both are presented in this paper. THD (%) value of optimization is less than non-optimization. The output voltage waveform for optimization is an ideal and smooth while non-optimization waveform is less smooth. This is due to the different switching angle estimation with the same modulation index.

VI. ACKNOWLEDGMENT

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