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Switching Angle Calculation By EP, HEP, HH And FF Methods For Modified 11-Level Cascade H-Bridge Multilevel Inverter

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Abstract: *In this paper the switching angles, from that the time required, to generate triggering pulses for IGBT switches of a single-phase Modified 11-Level Cascade H-Bridge Multilevel inverter is described by using Equal Phase (EP),Half Equal Phase (HEP), Half Height (HH) and Feed Forward (FF) methods. The proposed eleven level inverter is based on the H-bridge inverter. Instead of twenty IGBT switches as in conventional Cascade H-Bridge, this inverter requires only nine IGBT switches to obtain eleven level output. Because the numbers of switches are less, the cost and the complexity of the circuit is simple. The simulation results are presented using MATLAB/SIMULINK.*
Keywords*: Modified Cascade H-Bridge, Multilevel Inverter, EP, HEP, HH, FF and MATLAB/SIMULINK*

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I. Introduction

Multilevel inverters have become very popular in the last few years, due to their advantages over the conventional two level inverters, in producing sinusoidal waveform with low distortion, high quality and high efficiency. Many topologies of multilevel inverter have been proposed during the last three decades, aiming to construct a sinusoidal waveform. Three different major multilevel inverter structures have been reported in the literature: cascaded H-bridge inverter, diode clamped inverter and flying capacitor inverter. Nabae and Takahashi [1] introduced design analysis and control of a neutral point clamped (diode clamped) Pulse Width modulation inverter. The major problem with diode-clamped multilevel inverter configuration is the achievement of a balanced voltage supply within the DC link, and high numbers of clamping diodes are required as the number of levels increase. P. McGrath, D. G.Holmes [2] introduced Enhanced Voltage Balancing of a Flying Capacitor Multilevel Converter Using Phase Disposition (PO) Modulation. The main drawback with flying capacitor multilevel inverters is, voltage unbalancing of flying capacitors, which is the most serious problem. Malinowski, M.Gopakumar, K. Rodriguez, J. Perez, M.A. [3] introduced A Survey on Cascaded Multilevel Inverters. The major disadvantage of cascade multilevel inverter is, it needs a separate DC source for each H-Bridge.

Among them, cascaded H-bridge multilevel inverters have been received a great attention because of their merits such as minimum number of components, reliability, and modularity. In the viewpoint of obtaining a multilevel output voltage, the above conventional multilevel inverters will need more components resulted in complexity and cost increase. To minimize these drawbacks hybrid multilevel inverters were introduced in the last decades. [4]M.S. Usha Nandhini, N.Vinothini, R.Prakash were implemented Modified H-Bridge Nine Level Inverter with Low Switching Frequency. In their analysis they were implemented switching pattern for modified cascade H-bridge nine level inverter. In this paper the analysis includes switching angle and time calculation for 1-level Modified cascade H-bridge inverter by the following four methods.

1. Equal Phase (EP) Method.
2. Half Equal Phase (HEP) Method.
3. Half Height (HH) Method.
4. Feed Forward (FF) Method.

II. Proposed Multilevel Inverter

The proposed multilevel inverter is a modified cascade H-bridge multilevel inverter. Fig.1. shows the basic block diagram of the proposed multilevel inverter. The proposed system consists of a normal H bridge and some auxiliary switches. The proposed system is significantly advantageous over the conventional cascade H-bridge topology; less power switches, less anti parallel diodes, less power diodes and less switching losses for inverter of the same number of levels.

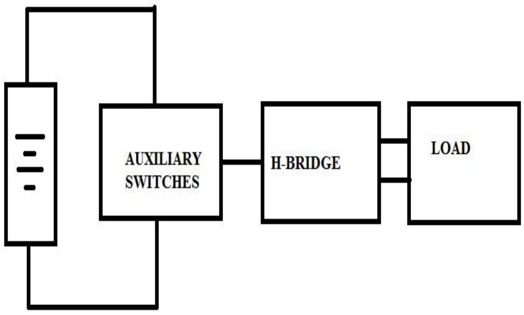

Fig.1 Basic block diagram

The proposed topology separates the output of the multilevel inverter into two parts. One part is named level generation part .The auxiliary switching circuit is responsible for level generating in positive polarity. The other part is called polarity generation part. The H-bridge will take the responsibility for generating the polarity of the output voltage. The simulink model of the proposed inverter is shown in Fig.2. As said above the proposed inverter consists of a normal H bridge and some auxiliary switches. A 11-level output waveform is generated at the output according to how the sources are being connected to the load. The H Bridge is operated normally to generate positive and negative polarity at the output. To generate the first level output, the voltage source V1 must be connected to the load. To obtain the second level output, both the sources (V1 and V2) must be connected to the load. The remaining sources (V3, V4 and V5) are also connected to the load in similar manner.[6]The switches are controlled in such a way that respective sources are connected to the load during desired time intervals. The switching pattern for the proposed 11-level inverter is shown in Fig.3

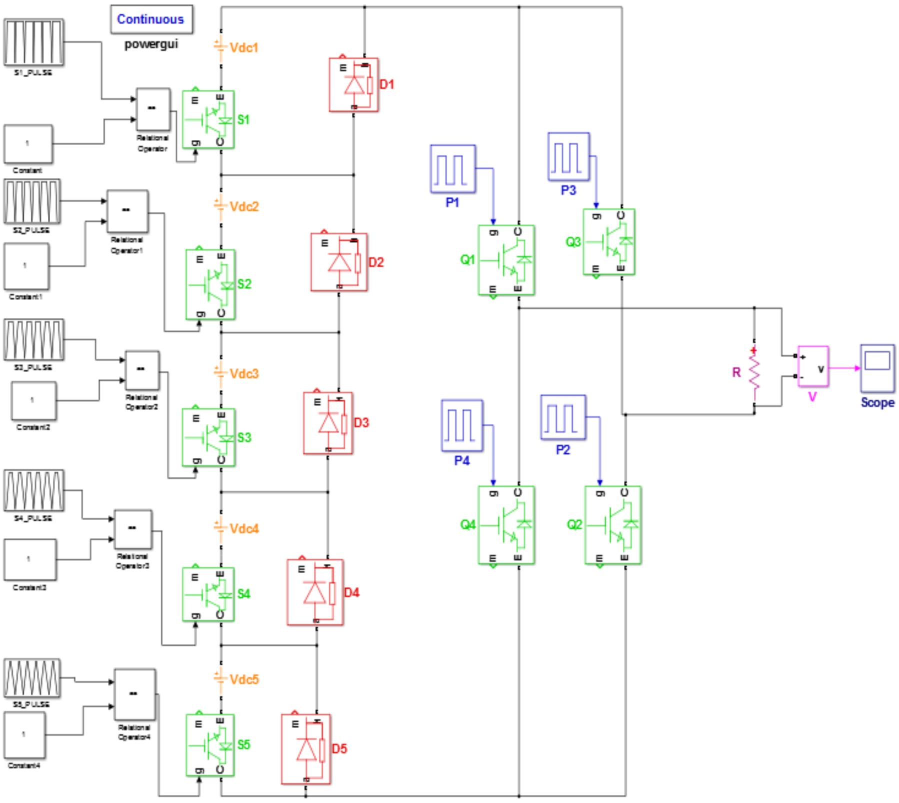

Fig.2 Simulink model of the proposed inverter

LEVEL	S1	S2	S3	S4	S5	Q1	Q2	Q3	Q4
0									
V									
2V									
3V									
4V									
5V									
4V									
3V									
2V									
V									
0									
-V									
-2V									
-3V									
-4V									
-5V									
-4V									
-3V									
-2V									
-V									
0									

Fig.3 switching pattern for the proposed inverter

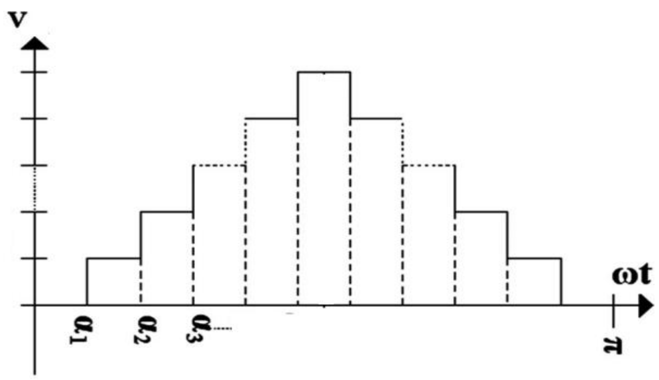

Fig.4 m-level output waveform

III. Methods For Determination Of Switching Angles

Switching angle is the moment of the voltage level change at the output. For an m-level waveform as shown in fig.4 there are 2(m-1) switching angles are needed. We call them as $\alpha_1, \alpha_2, \alpha_3, \ldots \alpha_{m-2}, \alpha_{m-1}$. Since the sine wave is a symmetrical waveform, as shown in fig., the negative half cycle is centrally symmetrical to its positive half cycle; and the waveform of the second quarter period is mirror symmetrical to the waveform of its first quarter period. So we call the switching angles in the first quadrant period i.e., 0^0-90^0 as main switching angles.

Main Switching Angles in the first quarter of the sine wave (i.e., 0^0 to 90^0)**:**

$\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_{(m-1)/2}$ ………… (1)

The switching angles in the second quarter of the sine wave(i.e., 90^0 to 180^0) are:

$\alpha_{(m+1)/2} = \Pi - \alpha_{(m-1)/2}, \Pi - \alpha_{(m-2)/2}, \ldots \Pi - \alpha_1$ ....(2)

The switching angles in third quadrant of the sine wave (i.e.,180^0 to 270^0) are

$\alpha_{m} = \Pi + \alpha_1, \ldots, \Pi + \alpha_{(m-1)/2}$ …………….(3)

The switching angles in the fourth quadrant (i.e.,270^0 to 360^0) are

$\alpha_{(3m-1)/2} = 2\Pi - \alpha_{(m-1)/2}, \ldots 2\Pi - \alpha_1$ ……………(4)

From the above analysis it was concluded that we need to determine only the main switching angles (i.e., from 0^0 to 90^0), the other switching angles (i.e., from 90^0 to 360^0) can be obtained from the main switching angles in the first quadrant. The main switching angles of the proposed inverter are determined from the following methods.

3.1. Equal Phase (EP) Method:
In the equal phase method the switching angles are distributed averagely in the range 0-Π.The main switching angles are obtained by the formula given below:

$\alpha_i = i * 180^0/m$ where i=1, 2,…………. (m-1)/2 ………………….. (5)

The main switching angles, by EP method, of the proposed 11-level inverter are determined from the equation (5)

$\alpha 1=16.36^0$, $\alpha 2=32.72^0$, $\alpha 3=49.09^0$, $\alpha 4=65.45^0$, $\alpha 5=81.81^0$

The other switching angles in second, third and fourth quadrants of sine wave are derived from the main switching angles according to the equations (2), (3) and (4). Table 1 shows the total switching angles required to get the sinusoidal wave shape by EP method.

3.2 Half Equal Phase (HEP) Method:
The waveform obtained from the EPM method looks like a triangle waveform, so to get some better output waveform, another method called [5]Half Equal Phase Method (HEPM) is established, by this approach we can get better and reduced harmonic output waveform. The main switching angles are in the range 0^0-90^0, which are obtained by the formula given below.

$\alpha_i = i * 180^0/(m+1)$ where i=1, 2,……… (m-1)/2 ………………(6)

For the proposed 11-level inverter the main switching angles, by HEP method, are calculated from the equation (6).

$\alpha 1=15^0$, $\alpha 2=30^0$, $\alpha 3=45^0$, $\alpha 4=60^0$, $\alpha 5=75^0$

After that the other switching angles are derived from the above main switching angles, according to the equations (2), (3) and (4). And are tabulated in Table 2

Table 1 Switching angles by EP method

ANGLE(α)	TIME
0^0	0.0000
$16.36^O(\alpha 1)$	0.0009
$32.72^O(\alpha 2)$	0.0018
$49.09^O(\alpha 3)$	0.0027
$65.45^O(\alpha 4)$	0.0036
$81.81^O(\alpha 5)$	0.0045
$98.18^O(\alpha 6)$	0.0054
$114.54^O(\alpha 7)$	0.0063
$130.90^O(\alpha 8)$	0.0072
$147.27^O(\alpha 9)$	0.0081
$163.63^O(\alpha 10)$	0.0090
$196.36^O(\alpha 11)$	0.0109
$212.72^O(\alpha 12)$	0.0118
$229.09^O(\alpha 13)$	0.0127
$245.45^O(\alpha 14)$	0.0136
$261.81^O(\alpha 15)$	0.0145
$278.18^O(\alpha 16)$	0.0154
$294.54^O(\alpha 17)$	0.0163
$310.90^O(\alpha 18)$	0.0172
$327.27^O(\alpha 19)$	0.0181
$343.63^O(\alpha 20)$	0.0190
360^O	0.02

Table-2 Switching angles by HEP method

ANGLE(α)	TIME
0^0	0.0000
$15^0(\alpha 1)$	0.0008
$30^0(\alpha 2)$	0.0016
$45^0(\alpha 3)$	0.0025
$60^0(\alpha 4)$	0.0033
$75^0(\alpha 5)$	0.0041
$105^0(\alpha 6)$	0.0058
$120^0(\alpha 7)$	0.0066
$135^0(\alpha 8)$	0.0075
$150^0(\alpha 9)$	0.0083
$165^0(\alpha 10)$	0.0091
$195^0(\alpha 11)$	0.0108
$210^0(\alpha 12)$	0.0116
$225^0(\alpha 13)$	0.0125
$240^0(\alpha 14)$	0.0133
$255^0(\alpha 15)$	0.0141
$285^0(\alpha 16)$	0.0158
$300^0(\alpha 17)$	0.0166
$315^0(\alpha 18)$	0.0175
$330^0(\alpha 19)$	0.0183
$345^0(\alpha 20)$	0.0191
360^0	0.02

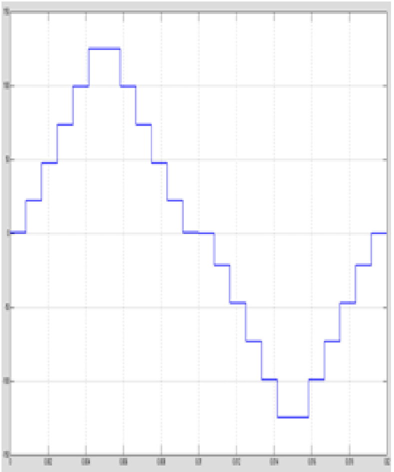

Fig.5 output waveform by EP method

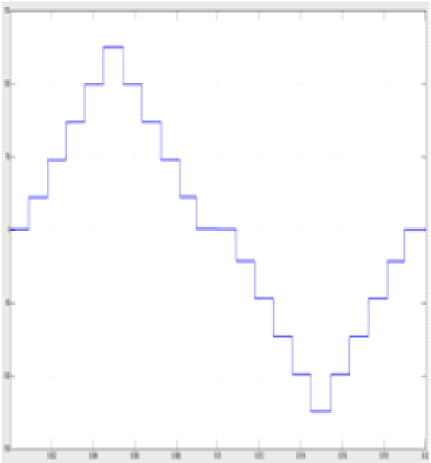

Fig.6 output waveform by HEP method

The obtained output waveforms of the proposed inverter by EP and HEP methods are shown in the Fig.5 and Fig.6 respectively. And also the THD analysis of the output waveforms by both the methods are shown in the Fig.7 & Fig.8.

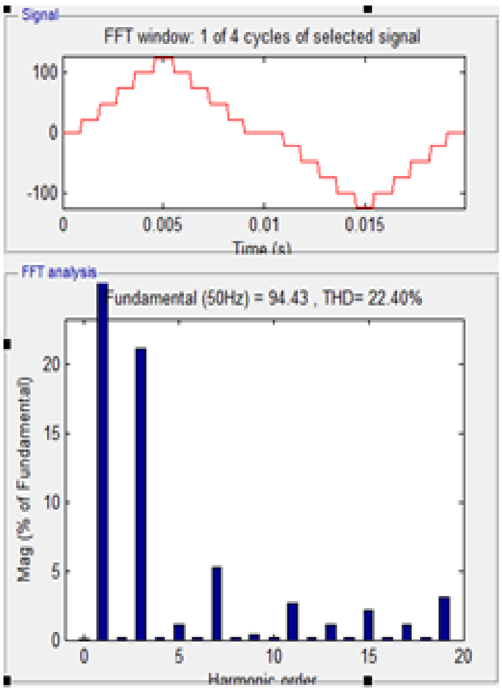

Fig.7 THD analysis by EP method

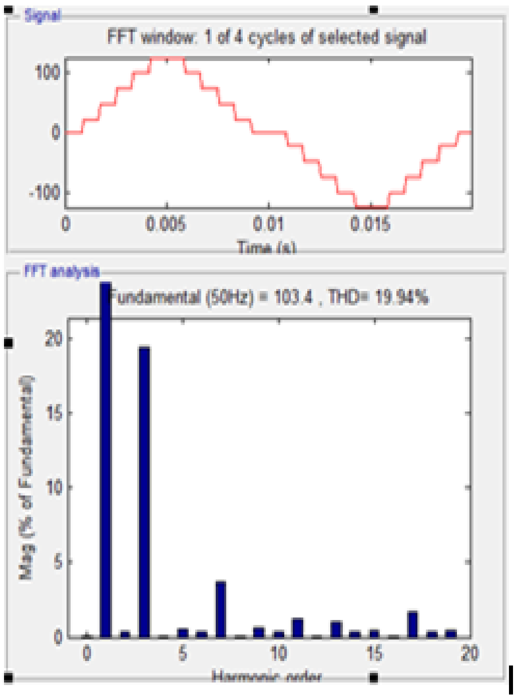

Fig.8 THD analysis by HEP method

3.3 Half Height (HH) Method:

In the above two methods the switching angles are arranged in a simple manner, but the waveform at the output is not a sine wave shape. According to the sine function a new method called [5] Half Height Method (HEM) was established to determine new switching angles. The main switching angles are obtained from the following formula.

$\alpha_i = \sin^{-1}(\frac{2i-1}{m-1})$ where i=1, 2,…………(m-1)/2 ……………………..(7)

In this method the main switching angles of the proposed 11-level inverter are

$\alpha1=5.74^0$, $\alpha2=17.46^0$, $\alpha3=30.00^0$, $\alpha4=44.43^0$, $\alpha5=64.16^0$

The other switching angles are derived from the main switching angles according to the equations (2), (3) and (4). Table3 shows the total switching angles, by HH method, needed to get the sinusoidal wave shape.

3.4 Feed Forward (FF) Method:

In the above three methods, we can observe that there are wider gaps between the positive half-cycle and negative half-cycle. In order to reduce the gaps in between the positive half cycle and negative half-cycle, another approach called the [5]Feed Forward Method (FFM) was established to find the main switching angles. The main switching angles are determined by the following formula.

$\alpha_i = \frac{1}{2}\sin^{-1}(\frac{2i-1}{m-1})$ where i=1, 2,………… (m-1)/2………………………(8)

The main switching angles, by FF method, of the proposed 11-level inverter are

$\alpha1=2.87^0$, $\alpha2=8.73^0$, $\alpha3=15^0$, $\alpha4=22.21^0$, $\alpha5=32.08^0$

After that the other switching angles are derived from the main switching angles, by using equations (2), (3) and (4). Table4 shows the total switching angles, of the proposed inverter, by FF method.

Table 3 Switching angles by HH method

ANGLE(α)	TIME
0^0	0.0000
5.74 ^{O}(α1)	0.0003
17.46 ^{O}(α2)	0.0009
30.00 ^{O}(α3)	0.0016
44.43 ^{O}(α4)	0.0024
64.16 ^{O}(α5)	0.0035
115.84 ^{O}(α6)	0.0064
135.57 ^{O}(α7)	0.0075
150.00 ^{O}(α8)	0.0083
162.54 ^{O}(α9)	0.0090
174.26 ^{O}(α10)	0.0096
185.74 ^{O}(α11)	0.0102
197.46 ^{O}(α12)	0.0109
210.00 ^{O}(α13)	0.0116
224.43 ^{O}(α14)	0.0124
244.16 ^{O}(α15)	0.0135
295.84 ^{O}(α16)	0.0164
315.57 ^{O}(α17)	0.0175
330.00 ^{O}(α18)	0.0183
342.54 ^{O}(α19)	0.0190
354.26 ^{O}(α20)	0.0196
360 ^{O}	0.02

Table 4 Switching angles by FF method

ANGLE(α)	TIME
0^0	0.0000
2.87 ^{O}(α1)	0.0001
8.73 ^{O}(α2)	0.0004
15.00 ^{O}(α3)	0.0008
22.21 ^{O}(α4)	0.0012
32.08 ^{O}(α5)	0.0017
147.92 ^{O}(α6)	0.0082
157.79 ^{O}(α7)	0.0087
165.00 ^{O}(α8)	0.0091
171.27 ^{O}(α9)	0.0095
177.13 ^{O}(α10)	0.0098
182.87 ^{O}(α11)	0.0101
188.73 ^{O}(α12)	0.0104
195.00 ^{O}(α13)	0.0108
202.21 ^{O}(α14)	0.0112
212.08 ^{O}(α15)	0.0117
327.92 ^{O}(α16)	0.0182
337.79 ^{O}(α17)	0.0187
345.00 ^{O}(α18)	0.0191
351.27 ^{O}(α19)	0.0195
357.13 ^{O}(α20)	0.0198
360 ^{O}	0.02

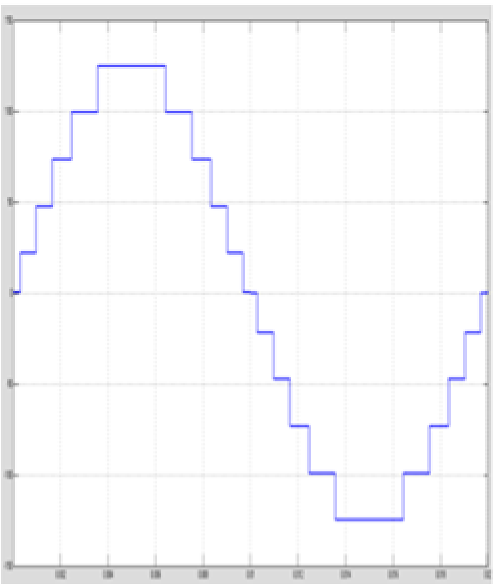

Fig.9 output waveform by HH method

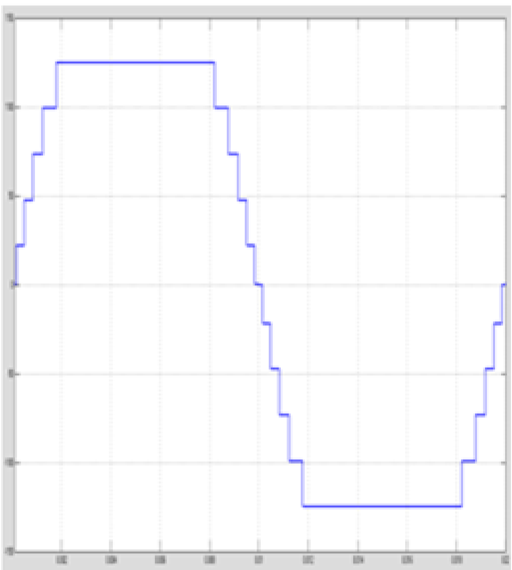

Fig.10 output waveform by FF method

The proposed inverter output voltage waveform by HH and FF methods are shown in the Fig.9 and Fig.10 respectively. And also the THD analysis of the output waveforms by both the methods are shown in the Fig. 11 & Fig.12 respectively.

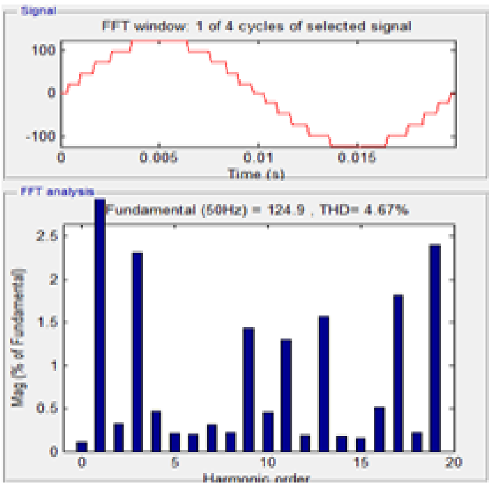

Fig.11 THD analysis by HH method

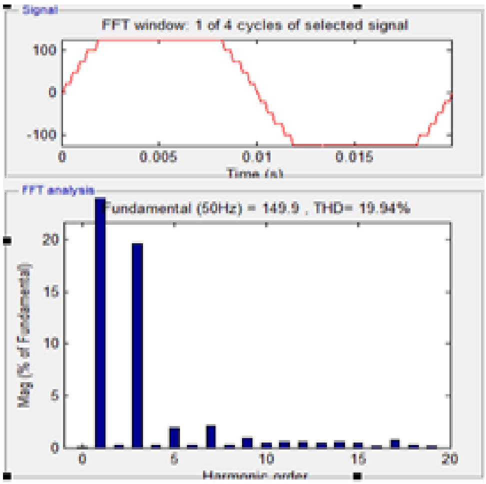

Fig.12 THD analysis by FF method

The THD analysis of the output waveform by EP, HEP, HH and FF methods are compared and are shown in table-5.From the comparison table, we observed that the HH method attains the least THD (i.e. 4.67%) compared to EP,HEP and FF methods.

Table 5 THD Comparison Table

Type of Method	%THD
EP	22.40
HEP	19.94
HH	4.67
FF	19.94

IV. Conclusion

In this paper EP, HEP, HH and FF methods have been proposed to find switching angles for Modified 11-level cascade H-bridge multilevel inverter. By observing above results, we concluded that by Half Height (HH) method we obtained better harmonic spectrum compared to other three methods, because the output waveform obtained by HH method is nearer to the sinusoidal. The results were obtained by using Matlab/Simulink to validate the design.

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