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Multi Level Inverter THD minimization by Non-Linear Programming Interior Point Method

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Abstract: In this paper, a Non-linear Programming Interior Point Method is proposed to determine the optimum switching angles for a Multilevel Inverter to reduce the It's Total Harmonic Distortion. First, a 11 level cascaded H- bridge multilevel inverter is implemented in MATLAB simulink. Then a Non-linear Programming Interior Point method algorithm is developed in MATLAB to find the optimum switching angles. Proposed algorithm is applied to 7 level, 11 level and 15 level inverters.

Keywords: Cascaded H-bridge Inverter, Multi Level Inverters , Non Linear Programming, Interior Point Method.

I. INTRODUCTION

Numerous industrial applications have begun to require high power apparatus in recent years. To achieve high power applications Multilevel inverters have drawn increasing attention, especially in the distributed energy resources area, because several batteries, fuel cells, solar cells, or rectified wind turbines or micro-turbines can be connected through a multilevel inverter to feed a load or interconnect to the ac grid without voltage balancing problems. In addition, multilevel inverters have a lower switching frequency than standard PWM inverters and thus have reduced switching losses, higher efficiency, and electromagnetic compatibility.

The general function of the multilevel inverter is to synthesize a desired voltage from several levels of dc voltages. As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches a desired waveform. Also, as more steps are added to the waveform, the harmonic distortion of the output wave decreases approaching zero as the number of levels increases.

The term “multilevel” starts from three levels. Subsequently, several multilevel converter topologies have been developed. However, the elementary concept of a multilevel converter to achieve high power is to use series of power semiconductor switches with several low voltage sources to perform the power conversion by synthesizing a stair case voltage waveform. Capacitors, batteries and renewable energy sources can be used as the multiple dc in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the ratings of the DC voltage sources to which they are connected.

There are three reported capacitor voltage synthesis based multilevel converters: Ddiode-clamp converter, Flying-capacitors converter and Cascaded-inverters with separated dc sources converter.

Due to the great demand of medium voltage high power inverters, the cascaded inverter has drawn tremendous interest ever since. The output waveforms of multilevel inverters are in a stepped form resulting in reduced harmonics compared to a square-wave inverter. To reduce the harmonics further, different multilevel sinusoidal PWM and space-vector PWM schemes are suggested in the literature. However, PWM techniques increase the control complexity and the switching frequency. Another approach to reduce the harmonics is to calculate the switching angles in order to eliminate certain order harmonics or THD. The mathematical theory of resultants can be used to compute the optimum switching angles. These expressions were high order polynomials that could not be solved when the number of levels in the multilevel converter became large. In this paper, easy method of calculating optimum switching angles is proposed by Non-linear Programming Interior Point Method.

II. CASCADED H-BRIDGE INVERTER

Cascaded H-Bridge inverter consists of a series of H-bridge (single phase, full bridge) inverter units. The general structure of multilevel inverter is to synthesize a desired voltage waveforms from several separate DC sources (SDCS)s which may be obtained from batteries, fuel cells or solar cells. Fig 1 shows the basic structure

of a single phase cascaded H-bridge inverter with SDCSs. Each SDCS is connected to an H-bridge inverter. The AC terminal voltages of different level inverters are connected in series. Unlike Diode clamped or flying capacitors inverter, the cascaded inverter does not require voltage clamping diodes or voltage balancing capacitors.

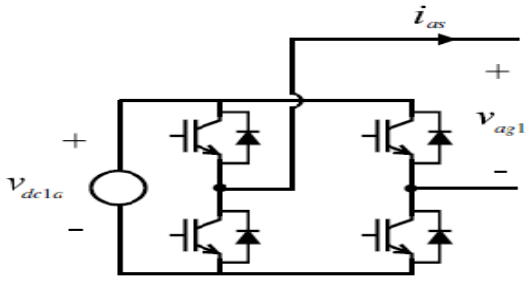
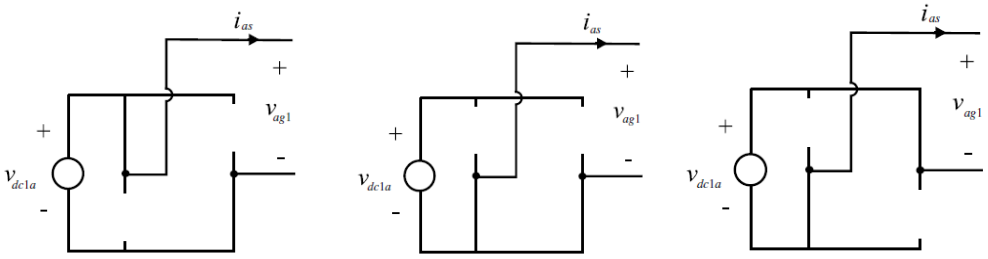


Fig 1 Single H-bridge cell topology.



Switching state S1 = 0 Vag1 = -Vdcla

Switching state S2 = 1 Vag1 = 0

Switching state S3 = 2 Vag1 = Vdcla

Fig 2 switching states of H-bridge cell

Figure 2 illustrates the switching states of one cascaded H-bridge topology which produces three unique output voltages -Vdcla , 0 ,Vdcla . In accordance with the convention used here, the lowest switching state (S1 = 0) will be labelled state 0 and for the switching states S2 = 1, S3 = 2 produces output voltages Vag1 = 0, Vag1 = Vdcla respectively.

The Fig. 3 shows the staircase 2m+1 levels output voltage of inverter where m is the number of separated DC sources in the one leg of H-bridge inverter. Three phase configuration can be formed by connecting three number of inverters in Y or Δ. In the terms of eliminating undesired higher order harmonics, switching angels shown in Fig. 2.5 must be calculated such that the voltage total harmonic distortion reduces to minimum.

2.1. Principle and operation

The AC output of each level's full-bridge inverter is connected in series such that the synthesized voltage waveform is the sum of all of the individual inverter outputs. The number of output phase voltage levels in a cascade multilevel inverter is then 2s + 1

Where S = number of dc sources

m = number of levels

For an 11-level cascaded multilevel inverter with five SDCSs and five full bridges is shown in Figure 4.With enough levels and an appropriate switching algorithm, the multilevel inverter results in an output voltage that is almost sinusoidal

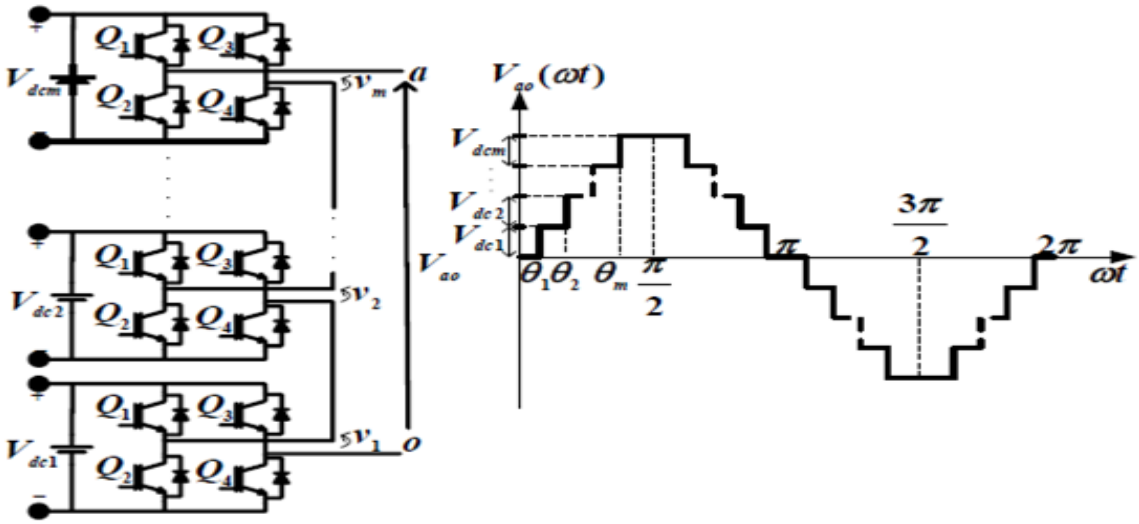


Fig 3 A 2m+1 levels H-bridge inverter structure with m separated dc sources and the stair case output phase voltage

Figure 4 also shows the synthesized phase voltage waveform of a 7 level cascaded inverter with three SDCSs. The phase output voltage is synthesized by sum of five inverter output voltages Vao = V1+V2+V3+V4+V5. Each bridge could produce voltages of 0, +Vdc and –Vdc which depend on the state of four power switches, Q11, Q12, Q13 and Q14. Using the fig 2.6 turning on Q11 and Q13 yields Vdc, turning on Q12 and Q14 yields -Vdc turning on of any two switches of same leg yields 0 voltage which is represented in table 2.1. Similarly AC output voltage at each level can be obtained in the same manner.

Table 2.1 Switching states of each cascaded H-bridge inverter

Q11	Q12	Q13	Q14	O/p Voltage
1	0	1	0	Vdc
1	1	0	0	0
0	0	1	1	0
0	1	0	1	-Vdc

Each cascaded H-bridge inverter generates a quasi square wave output by shifting its positive and negative leg switching timings. It should be noted that each switching device always conducts at 180 degrees (or half cycle).

Together, all cascaded H-bridge forms the output voltage waveform, as shown in Figure 4. For THD optimization, the switching angles θ1, θ2, θ3, θ4, θ5 must be selected so that THD is minimized.

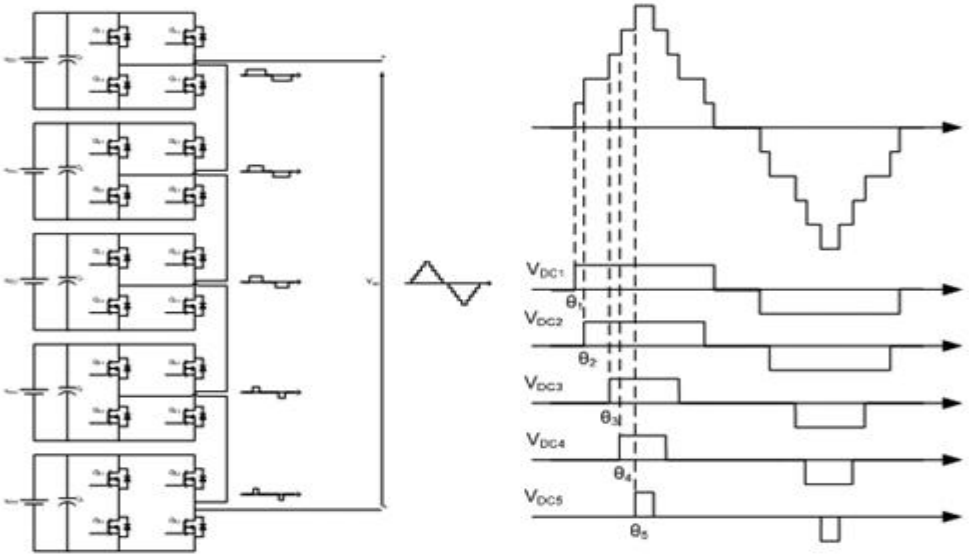


Figure 4: 11 level inverter and output waveforms

III. INTERIOR POINT METHOD

Transform the point x^k from a feasible region in x-space to a point y^k in a feasible region in y-space. The direction of search d^k needs to be found out; then the step size α^k is to be found out. New point obtained, $y^{k+1} = y^k + \alpha^k d^k$. Next, we translate y^{k+1} to x^{k+1} and check if the stopping criteria is satsified. If No, we repeat the above steps or else conclude on the optimal point x^* *as* x^{k+1}

3.2.1 Affine Scaling Algorithm:

Problem Statement : minimize $C^T x$;

subjected to Ax =b ; x ≥ 0 (1)

Step 1: Start with an interior point x^0

Find $X^k = diag(x^k)$ (2)

$$\mu^k = (AX^{k^2}A^T)^{-1}AX^{k^2}C \quad (3)$$

Step 2: Check Stopping Criteria

While ($C^T x^k - b^T \mu^k) > \varepsilon$; (4)

go to Step 3 if No, conclude x^k as optimal point

Step 3: Transform the current problem in x-space to y-space so that the current point is close to the centre of the feasible region .

Where; $y^k = (X^k)^{-1}x^k$ (5)

Use Projected Steepest Descent direction to take a step in y –space.

$y^{k+1} = y^k + \alpha^k d^k$ (6)

Where, direction of search $d^k = -(I - X^k A^T (AX^{k^2}A^T)^{-1}AX^k)X_c^k$ (7)

step length $\alpha^k = 0.9 * \min\left(\frac{-1}{d_j^k}\right)$ (8)

Step 4: Translate back y^{k+1} *to* x^{k+1}

$x^{k+1} = X^k(1 + \alpha^k d^k)$; $X^{k+1} = diag\ (x^{k+1})$ (9)

Find out $\mu^{k+1} = (AX^{k+1^2}A^T)^{-1}AX^{k+1^2}C$ (10)

If stopping criteria is satisfied, then $x^{k+1} = x^*$ or else Translate the point back to y-plane to find out next optimal point

Fiacco and Mc Cormick proposed the Logarithmic Barrier Function approach to include the inequality constraints into the objective function by means of a logarithmic barrier function to transform the Constrained Problem into an Unconstrained Problem.

Problem of Type : minimize f (x) subject to h(x) ≥ 0 is transformed as

Minimize f(x, μ^k) = f(x) - $\mu^k \sum_{i=1}^{p} lnh_i(x)$

Where μ^k is a barrier parameter which takes positive values, which is decreased to zero as the No.of Iterations progress. Initial barrier parameter can be started from 0.1 in Optimization Tool box in MATLAB.

Minimization of THD is the objective function. It can be obtained from the simulink diagram shown in figure 5. The control variables are the switching angles. The lower and upper bounds on these varibles is [0 90].

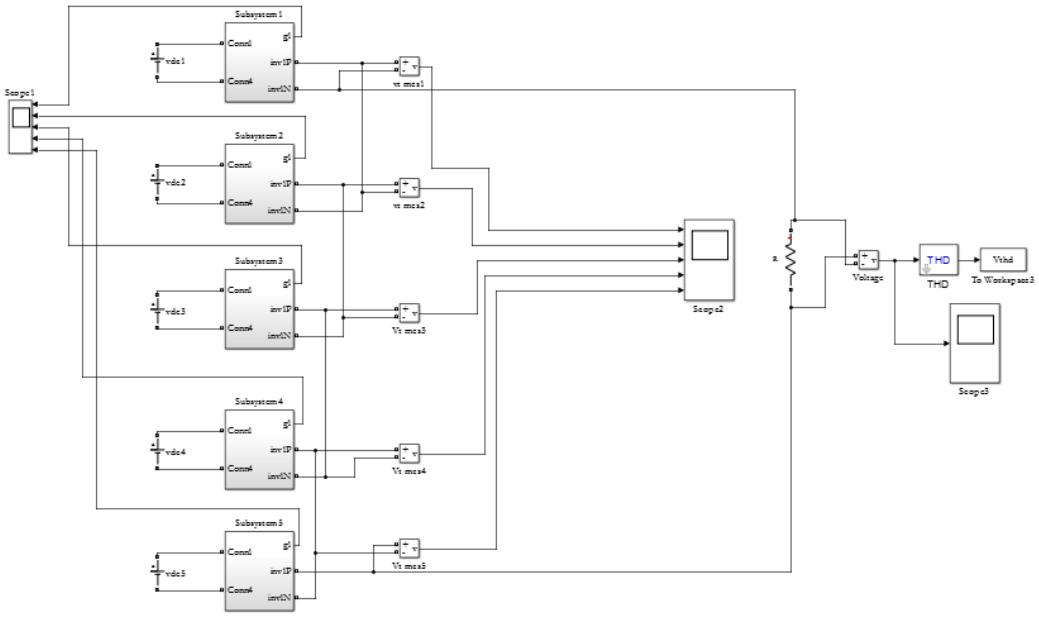


Figure 5: Simulink model of Cascaded H-bridge 11 level inverter.

IV. RESULTS AND DISCUSSION

All the simulations are done in MATLAB. The optimum switching angles calculated by the IP method are shown in Table 1. IP method reduced the THD to 13.74% in & level inverter is shown in Figure6. The voltage wave forms are shown in Figure 7.

Table 1: Optimum switching angles obtained by IP

θ_1	θ_2	θ_3
1.22	27.01	48.21

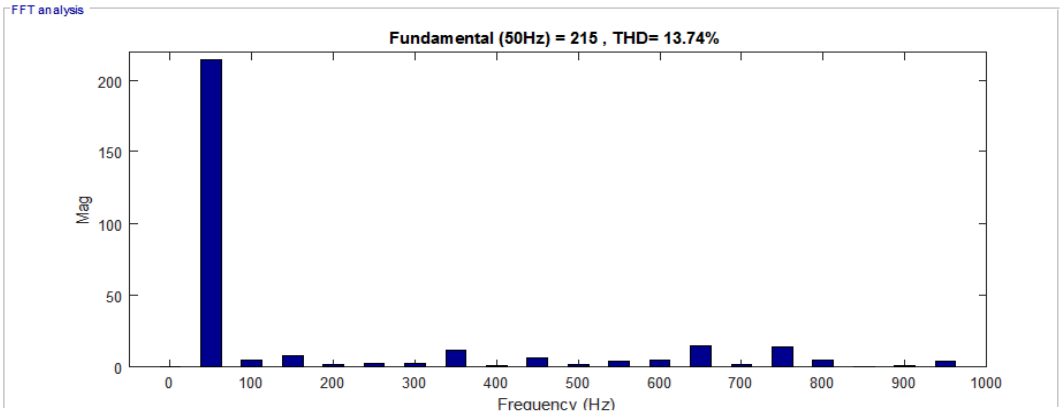


Figure 6: FFT analysis for 7 level inverter

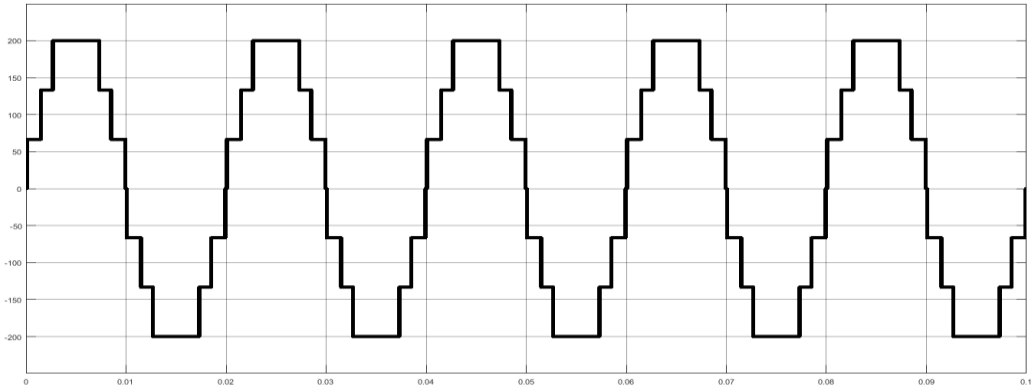


Figure 7: Output Voltage Wave forms after THD minimization for a 7 level inverter

The optimum switching angles calculated by the IP method are shown in Table 2. IP method reduced the THD to 7.23% in & level inverter is shown in Figure 8. The voltage wave forms are shown in Figure 9.

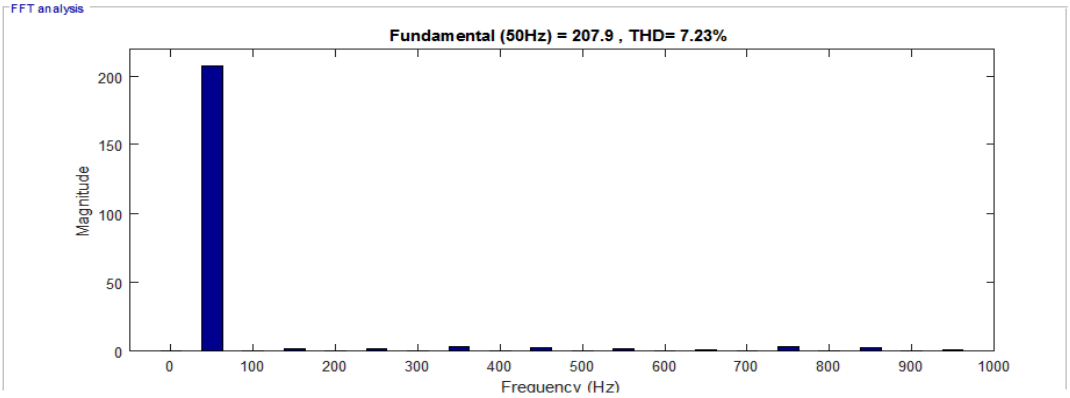


Figure 8: FFT analysis for 11 level inverter

Table 2: Optimum switching angles obtained by IP for the 11 level.

θ_1	θ_2	θ_3	θ_4	θ_5
5.49	16.68	28.58	42.05	59.46

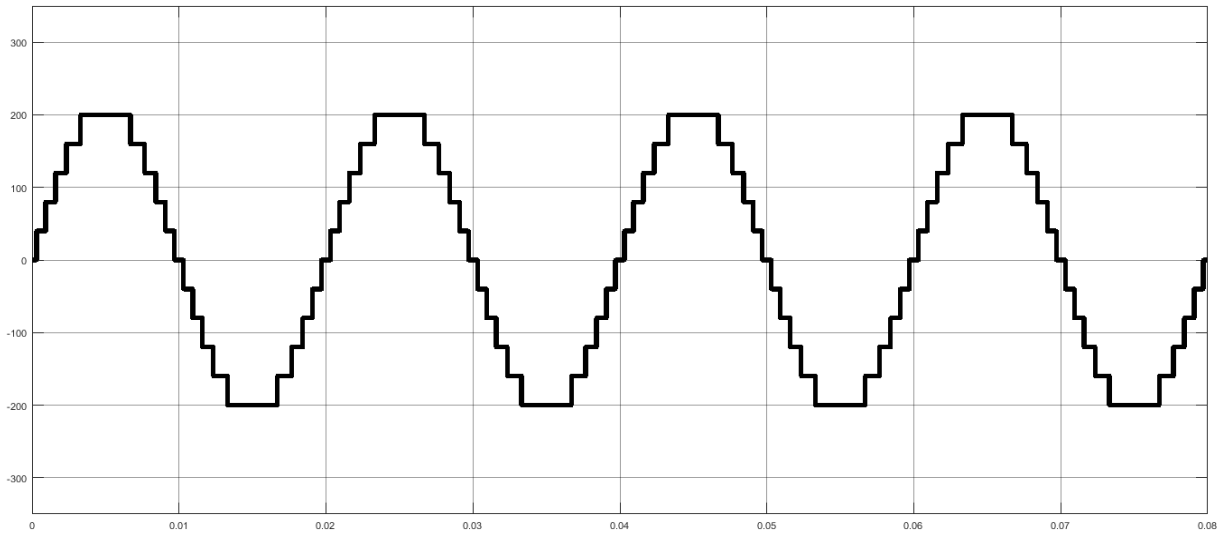


Figure 9: Output Voltage Wave forms after THD minimization for a 11 level inverter

The optimum switching angles calculated by the IP method are shown in Table 3. IP method reduced the THD to 5.32% in & level inverter is shown in Figure 10. The voltage wave forms are shown in Figure 11.

Table 3: Optimum switching angles obtained by IP for the 15 level.

θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7
3.97	11.99	20.26	29.01	38.57	49.65	64.25

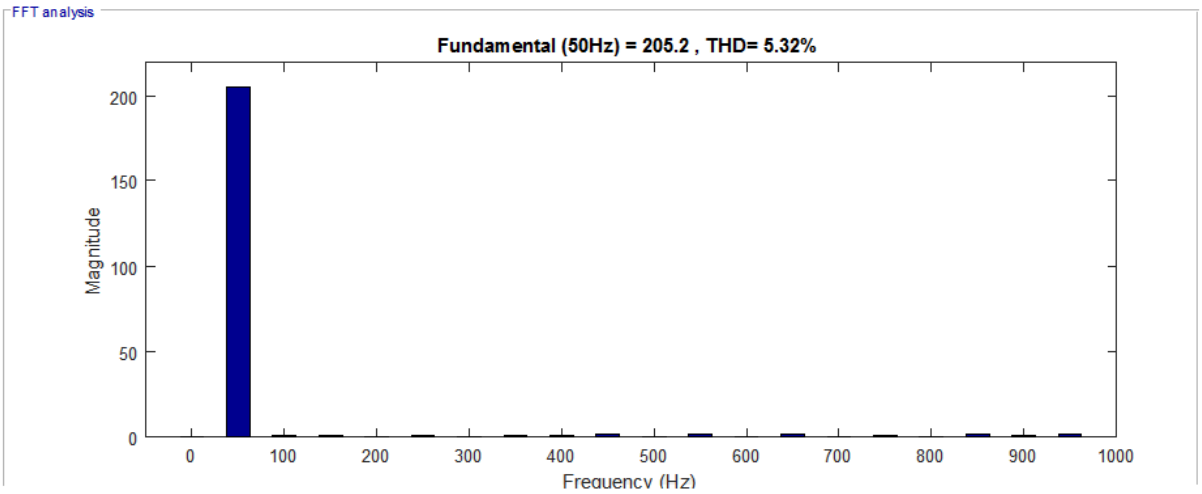


Figure10: FFT analysis for 15 level inverter

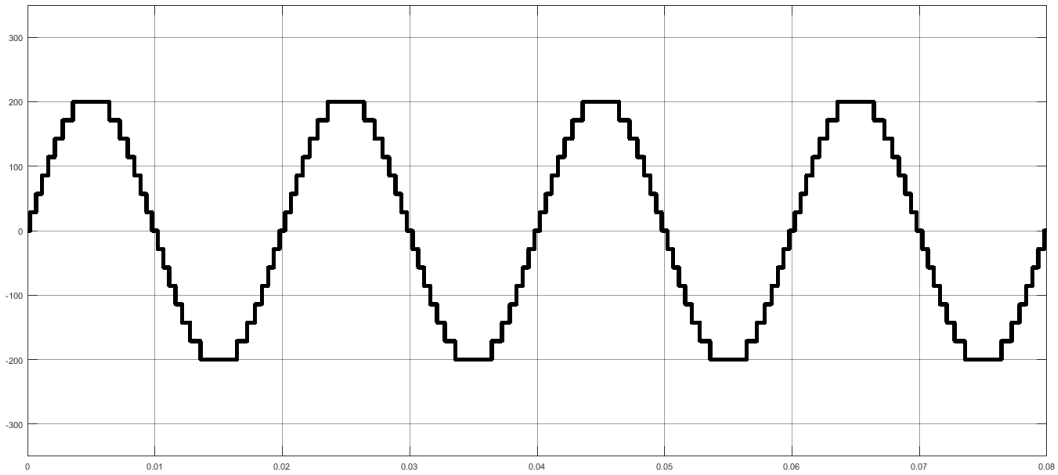


Figure11 : Output Voltage Wave forms after THD minimization for a 15 level inverter

V. CONCLUSION

A Non-linear Programming Interior Point Method is proposed to find optimum switching angles for 7 level,11 level and 15 level cascaded H-Bridge multi level inverter. The simulation results show that Proposed method is effective in reducing the THD for 7 level, 11 level and 15 level inverters. It can also be observed from the results that as the levels are increasing, THD is reducing.

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