Harmonic Minimization Using Newton Raphson Method

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***Abstract*—**In this paper, a Newton Raphson iterative technique is applied on cascaded multilevel inverter in order to determine the switching angles that eliminates specified higher order harmonics while maintains the required fundamental output voltage. This technique can be applied to any number of levels of multilevel inverters. A nine-level inverter is considered in this paper and the optimized switching angles are calculated in order to eliminate the lower order harmonics using SHE equations.

***Index Terms* – Cascaded H-Bridge Multilevel Inverters (CHB-MLIs), Newton– Raphson method (NR), Selective Harmonic Elimination (SHE), Total Harmonic Distortion (THD), Weighted Total Harmonic Distortion (WTHD).**

I. INTRODUCTION

Multilevel inverters from past two decades have attracted wide interest both in the scientific community and in the industries. The main reasons for high interest is that the multilevel inverters are a viable topology to implement controlled rotational movement in high-power application. It is depicted from the history of multilevel converters, some patent are found that shows multilevel inverter circuit have been around for more than 35 years. In 1975, a patent is appeared that defines the cascaded multi-level topology in which output is synthesize by series connection of H-Bridge in order to make a staircase ac output [1]. In 1981, a patent appeared about Neutral Point Clamped Topology which was extended to multilevel inverter application. In [2], first introduced the world about the topology, control and application of multilevel inverters. They presented the concept of multilevel converter, their basic three topologies i.e. Diode Clamped, Flying Capacitor and Cascaded H-Bridge [3]. The major issue is the lower order harmonic content that are present in the output voltage as it leads to instability to the system. For this, NR method is applied to calculate the switching angles that will eliminate the deadliest lower order harmonic by solving non-linear equations obtained from SHE.

II. CASCADED H-BRIDGE MULTILEVEL INVERTERS (CHB-MLI)

This topology is most widely used because of its simpler structure, lower switching losses, symmetric triggering and simple control. Fig.1 shows the single phase connection of n-level CHB-MLIs that are connected in cascaded fashion. Each cell has a DC voltage source with equal value of voltage i.e. 100V and it also consists of symmetric connection of IGBT switches which gives the nine-level output voltage that is shown in Fig.1 when triggered with optimized switching pulses. For nine-level four angles are to be measured i.e. $\alpha_1, \alpha_2, \alpha_3, \alpha_4$. Three phase connection is achieved by connected 3 single phase output either in star or delta form [4-5].

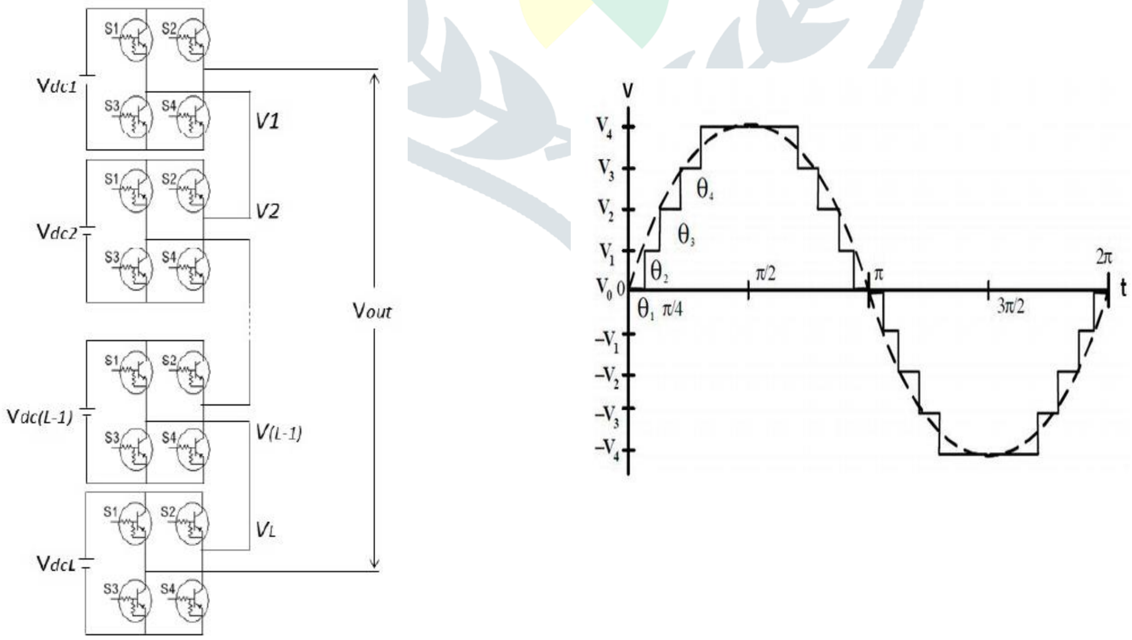

Fig.1 Cascaded n-level multilevel inverter and its output voltage

III. SELECTIVE HARMONIC ELIMINATION (SHE)

The main function of SHE equations is to eliminate the lower order odd harmonics i.e. 5th, 7th, 11th and so on or make these harmonics to allowable limit in order to improve the THD of output voltage. In this paper, three phase CHB-MLI is used so triplen harmonics are absent in the line-line voltage. Moreover, the output voltage has quarter symmetry, this leads to absence of even harmonics and

DC component. In MLIs there are different control techniques for controlling the output voltage i.e. low or fundamental and high switching frequency. The SHE is considered in low switching frequency technique. It is preferred over high switching frequency because of less losses in case of low switching [6-7]. From Fig.1 it can be clearly seen that all the switching angles are less than 90^0. The 5^{th}, 7^{th} and 11^{th} harmonics can be reduced to allowable limit by solving the non-linear equations and M is the modulation index.

$$\cos(\alpha_1^j) + \cos(\alpha_2^j) + \cos(\alpha_3^j) + \cos(\alpha_4^j) = 4M \quad (1)$$

$$\cos(5\alpha_1^j) + \cos(5\alpha_2^j) + \cos(5\alpha_3^j) + \cos(5\alpha_4^j) = 0 \quad (2)$$

$$\cos(7\alpha_1^j) + \cos(7\alpha_2^j) + \cos(7\alpha_3^j) + \cos(7\alpha_4^j) = 0 \quad (3)$$

$$\cos(11\alpha_1^j) + \cos(11\alpha_2^j) + \cos(11\alpha_3^j) + \cos(11\alpha_4^j) = 0 \quad (4)$$

These equations are highly non-linear in nature and it is solved by NR method in order to get desired values of switching signals for lower THD in the output voltage.

IV. THD & WTHD

Quality of output voltage waveform is measured by THD, which gives the total harmonic content in the output waveform and is defined as

$$THD = \frac{1}{V_1}\left(\sum_{n=2,3\ldots}^{\infty} V_n^2\right)^{1/2} \quad (5)$$

V_1= Fundamental component voltage (rms)
V_n= nth harmonic component (rms)
n= harmonic order

THD does not consider severity of lower order harmonics and treat all harmonic equally. In order to consider this Weighted Total Harmonic Distortion (WTHD) is used. It gives a better measurement of harmonic pollution by using the order of each harmonic component as its weight factor. Further index considers the severity of lower order of voltage harmonics and WTHD is defined by.

$$WTHD = \frac{1}{V_1}\left[\sum_{n=2,3\ldots}^{\infty}\left(\frac{V_n}{n}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

V. NEWTON RAPHSON METHOD (NR)

Newton-Raphson Method is a powerful iterative technique in solving the non-linear equations. This method is based on linear approximation principle. It starts with a random initial guess and then converges faster for most of the function irrespective of initial guess [8]. However, if the initial guesses are not close to the true roots, it may diverge also [9-10].

On the basis of x_0 , the iteration starts. If it will not converge to optimized solution, the value of x_0 is further improved by applying the following equation.

$$x_{n+1} = x_n - \frac{f(x)}{f'(x)} \quad (7)$$

Applying NR method for solving SHE equations problem is quiet easy. The following steps below summarize and explain the application of NR method in the case of 9- level inverter:

STEP 1:- Assume any random initial guess for switching angles (say α_0),

The switching angles matrix is:

$$\alpha^j = [\alpha_1^j \quad \alpha_2^j \quad \alpha_3^j \quad \alpha_4^j]^T \quad (8)$$

STEP 2: Start modulation index with zero.

STEP 3: Evaluate the non- linear system matrix F^j, the Jacobian matrix $\frac{\partial f^j}{\partial \alpha}$ and the harmonic amplitude matrix B represented below:

The non-linear system matrix,

$$F^j = \begin{bmatrix} \cos(\alpha_1^j) + \cos(\alpha_2^j) + \cos(\alpha_3^j) + \cos(\alpha_4^j) \\ \cos(5\alpha_1^j) + \cos(5\alpha_2^j) + \cos(5\alpha_3^j) + \cos(5\alpha_4^j) \\ \cos(7\alpha_1^j) + \cos(7\alpha_2^j) + \cos(7\alpha_3^j) + \cos(7\alpha_4^j) \\ \cos(11\alpha_1^j) + \cos(11\alpha_2^j) + \cos(11\alpha_3^j) + \cos(11\alpha_4^j) \end{bmatrix} \quad (9)$$

Jacobian matrix,

$$\frac{\partial f^j}{\partial \alpha} = \begin{bmatrix} -\sin(\alpha_1^j) & -\sin(\alpha_2^j) & -\sin(\alpha_3^j) & -\sin(\alpha_4^j) \\ -5\sin(5\alpha_1^j) & -5\sin(5\alpha_2^j) & -5\sin(5\alpha_3^j) & -5\sin(5\alpha_4^j) \\ -7\sin(7\alpha_1^j) & -7\sin(7\alpha_2^j) & -7\sin(7\alpha_3^j) & -7\sin(7\alpha_4^j) \\ -11\sin(11\alpha_1^j) & -11\sin(11\alpha_2^j) & -11\sin(11\alpha_3^j) & -11\sin(11\alpha_4^j) \end{bmatrix} \tag{10}$$

Corresponding harmonic amplitude matrix,

$$B = [4M \quad 0 \quad 0 \quad 0]^T \tag{11}$$

The solutions must satisfy the following condition:

$$0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \alpha_4 \le \frac{\Pi}{2} \tag{12}$$

STEP 4: Compute correction Δα during the iteration using relation,

$$\Delta\alpha = \frac{\partial f^j}{\partial \alpha}(\alpha_j)(B - F^J) \tag{13}$$

STEP 5: Update the new switching angles as,

$$\alpha(k+1) = \alpha(k) + \Delta\alpha(k) \tag{14}$$

STEP 6: Applying following transformation switching angles can be calculated:

$$\alpha(k+1) = \cos^{-1}\left(abs\left(\cos\left(\alpha(k+1)\right)\right)\right) \tag{15}$$

STEP 7: Repeat step (3) to (6) for maximum number of iterations to attain error.
STEP 8: Increment m by a fixed step size.
STEP 9: Repeat step (2) to (8) for whole range of modulation index.

Like the other iterative methods, it is required for NR method to stop the iteration. Otherwise, it will not stop and go for searching the result. So, the iteration is automatically terminated in case of maximum iterations reached or if the change in switching angle is zero i.e.Δα=0.

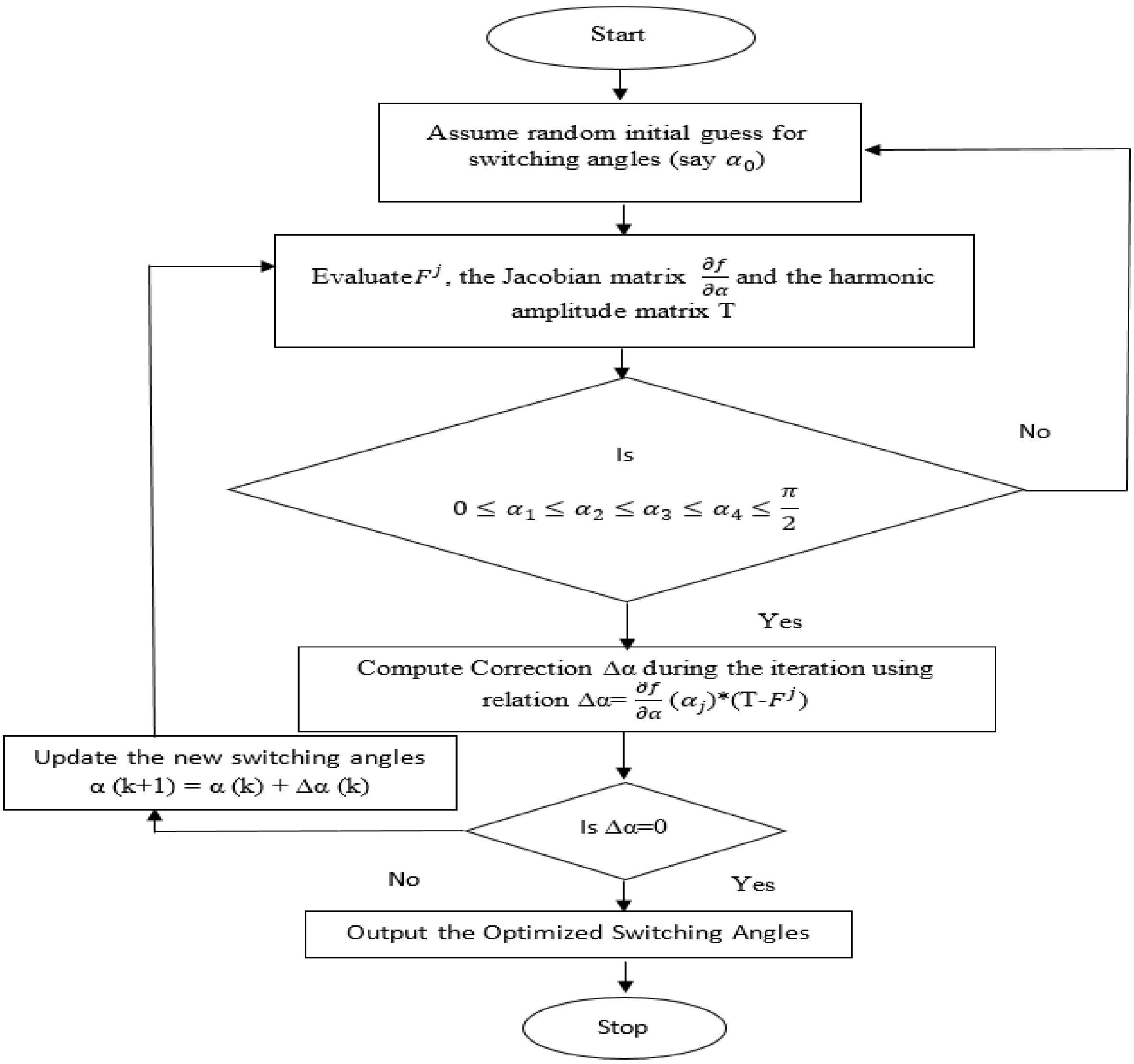

Fig.2 Flowchart of NR Method

VI. SIMULATION RESULTS AND DISCUSSIONS

Simulation of 9-level inverter has been done in MATLAB simulink. Optimized switching angles from the Newton Raphson Method are shown in Fig.3. The harmonic analysis for 9 level inverter is carried out with switching angles i.e. $\alpha_1 = 0.1282$, $\alpha_2 = 0.3934$, $\alpha_3 = 0.6951$ and α_4 =1.0571 at 0.69 modulation index using NR method. The voltages of the four dc voltage sources are 100V each. Fig.4 and Fig.5 shows the obtained line voltage and phase voltage waveforms for the optimal switching angles at 0.69 value of modulation index.

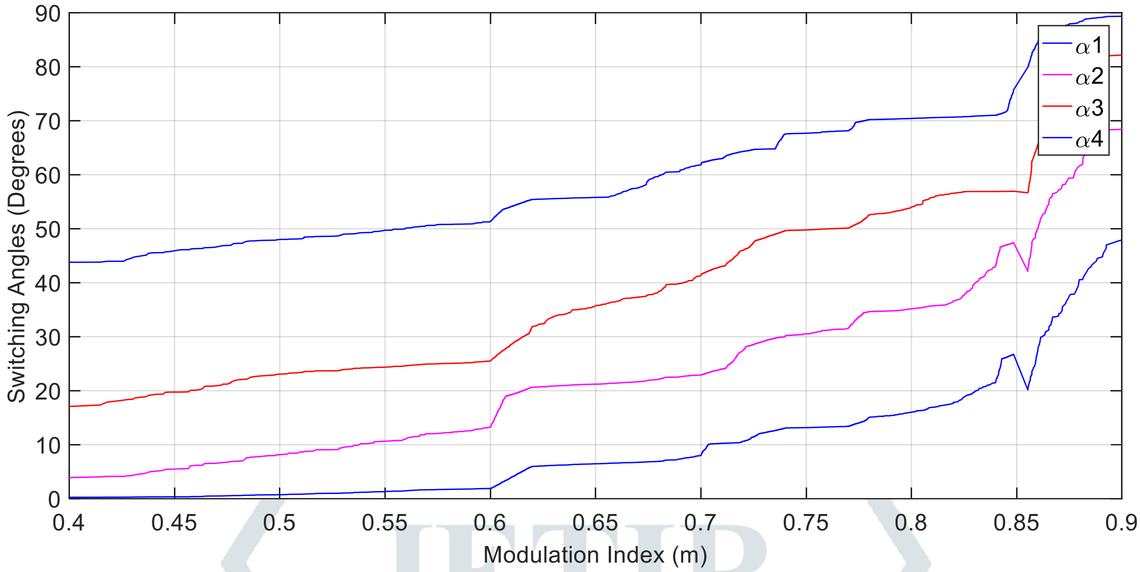

Fig.3 Optimized Switching Angles for 9-level CHBMLI using NR Method

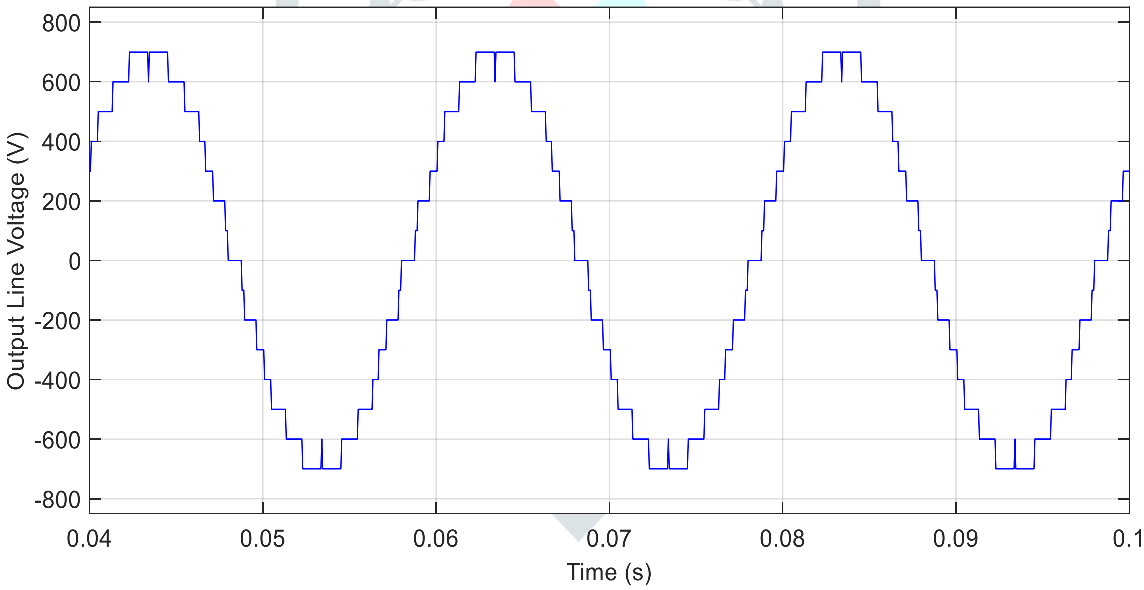

Fig.4 Output Line Voltage of 9-level inverter using NR Method for m=0.69

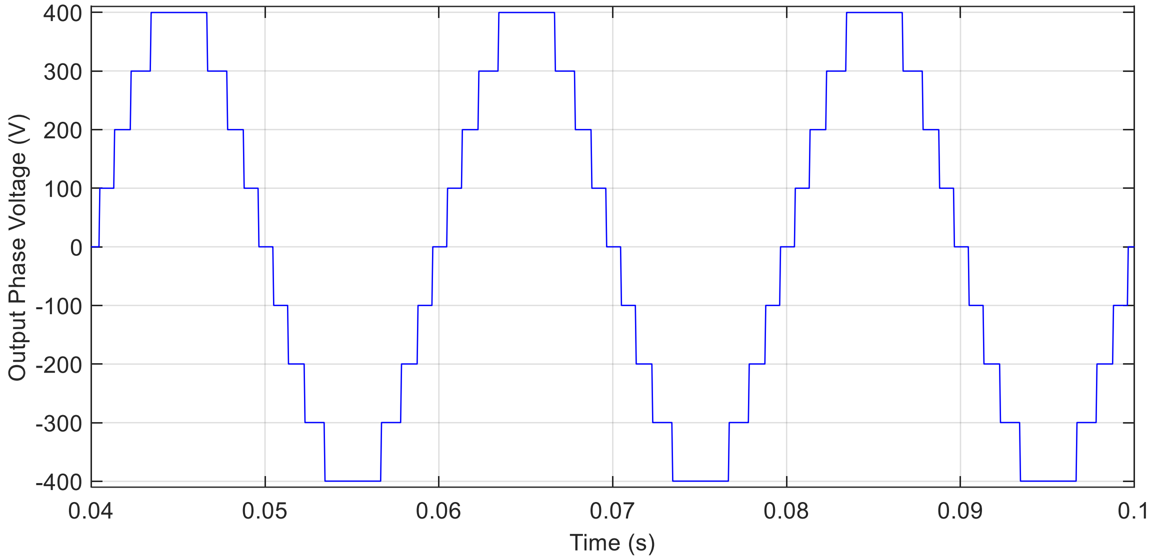

Fig.5 Output Phase Voltage of 9-level inverter using NR Method for m=0.69

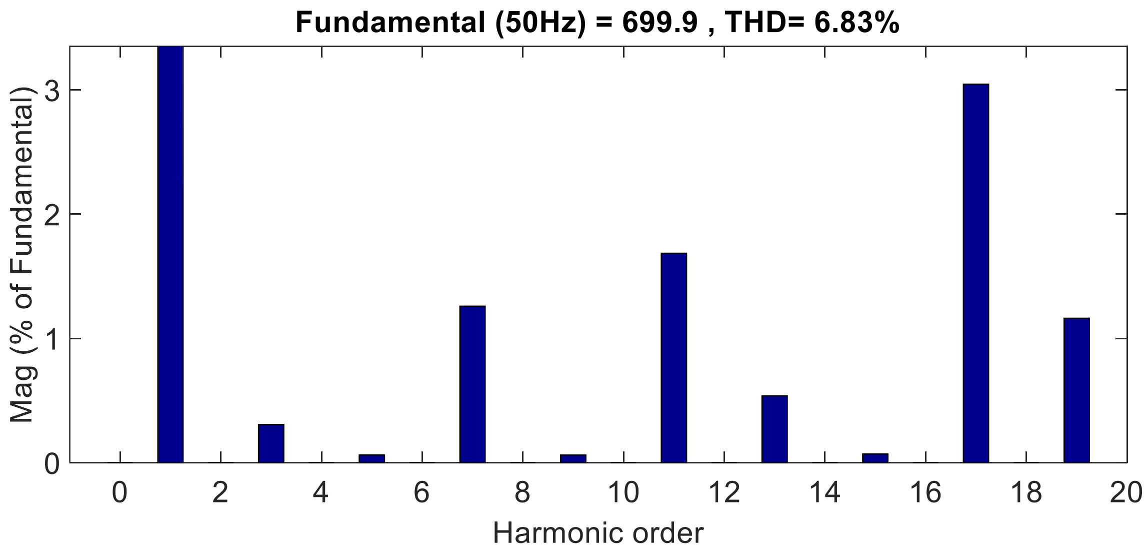

Fig.6 FFT Analysis of Line Voltage at m=0.69 for NR Method

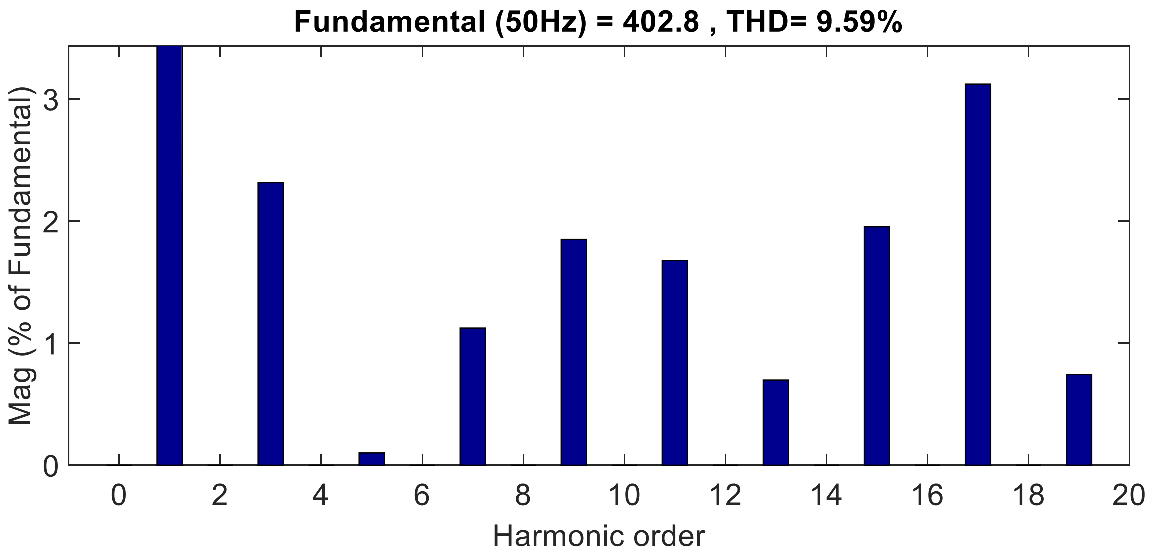

Fig.7 FFT Analysis of Phase Voltage at m=0.69 for NR Method

It can be seen from Fig.6 that, the minimum value of line voltage THD is 6.83%. It can be observed from the frequency spectrum of phase voltage shown in Fig.7 that, the value of THD is 9.59% at 0.69 value of modulation index and the triplen harmonics are very prominent. Since, in three phase load triplen harmonics are get eliminated in the line voltage.

The peak and RMS values of line voltage and phase voltage and their corresponding THD value (%) and harmonic content (%) upto 19th order for 9-level CHBMLI are given in Table 1.

Table 1 Magnitude of Harmonic Content (%) of 9-level CHBMLI for NR Method

LINE VOLTAGE (THD 6.83%) 699.9 peak (494.9 rms)				PHASE VOLTAGE (THD 9.59%) 402.8 peak (284.8 rms)			
Harmonic Order	Even Harmonic	Harmonic Order	Odd Harmonic	Harmonic Order	Even Harmonic	Harmonic Order	Odd Harmonic
0th	0.00	1th	100	0th	0.00	1th	100
2nd	0.00	3rd	0.31	2nd	0.00	3rd	2.31
4th	0.00	5th	0.06	4th	0.00	5th	0.10
6th	0.00	7th	1.26	6th	0.00	7th	1.12
8th	0.00	9th	0.06	8th	0.00	9th	1.85
10th	0.00	11th	1.69	10th	0.00	11th	1.68
12th	0.00	13th	0.54	12th	0.00	13th	0.70
14th	0.00	15th	0.07	14th	0.00	15th	1.95
16th	0.00	17th	3.05	16th	0.00	17th	3.12
18th	0.00	19th	1.16	18th	0.00	19th	0.74

The harmonic contents (%) shown in Table 1 depicts that, the magnitude of dc component and even harmonics are zero in all cases. All the odd harmonics upto 15th harmonic are less than 3% in the line voltage. The deadliest harmonics 5th and 7th of the line voltage have reduced to 0.06% and 1.26% respectively.

From equation (6), it is found that WTHD in the line voltage is 0.32% while in the phase voltage it is 0.86% in 9-level CHB-MLI.

VII. CONCLUSION

Newton Raphson method is used for harmonic reduction in three phase 9-level inverter. From results, it can be clearly seen that the lower order harmonics are with in permissible limit and the overall THD is reduce to 6.83% in the output line voltage and corresponding WTHD in the output line voltage is 0.32% which is less than the phase voltage percentage. So, NR method works properly and can be further applied to higher levels of MLIs by solving the transcendental equations obtained from SHE.

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