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Comparative Analysis of NR and TBLO Algorithms in Control of Cascaded MLI at Low Switching Frequency

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Abstract

To control multilevel inverters in medium voltage drives applications which operate at a power level of mega watts, modulation control strategies at high switching frequency are not preferable due to high thermal losses and poor converter efficiency. Instead, fundamental switching frequency technique such as selective harmonic elimination technique is one of the widely used methods. The non linear transcendental trigonometric SHE equations set which are formed in control of multilevel inverter are highly non linear in nature , hence it has been a challenging task for researchers to obtain feasible solution at desired value of modulation index. So far, in literature several techniques have been proposed to obtain the feasible switching angles in control of MLI with less %THD. All the proposed stochastic optimization techniques need the declaration of algorithmic specific parameters. This paper presents, comparative analysis of NR method with random initial guess and novel algorithm such as teaching learning based optimization technique to solve SHE equation set at different values of modulation index. To validate the proposed technique, a three phase CHB seven level inverter has been considered and the developed algorithms are tested at different modulation indices and comparative analysis have been carried out. MATLAB programming and SIMULINK environment has been considered to validate proposed method**.** The %THD produced at different values of modulation indices are complies with IEEE 519-1992 harmonic guidelines too.

Keywords: cascaded multilevel inverter; NR method; selective harmonic elimination technique; teacher learning based optimisation; THD

1. Introduction

Multilevel inverter technology is an emerging area in the past few decades as it posses the advantages of

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synthesizing higher, voltage levels with lower rating of semi conductor switch ratings for application in medium voltage and high power area. Such as medium voltage traction, medium voltage drives and hybrid electric vehicles, power quality. The commercial availability of multi level inverters in present market are classified to three topologies such as diode clamped MLI(DC MLI), Cascaded H-Bridge MLI(CHB MLI) and Flying capacitor MLI(FC MLI). Among all these topologies, Cascaded H-bridge MLI is generally preferred topologies for many industrial applications. The main limitations in the control of adjustable speed drives are poor converter efficiency and motor bearing failure. The main Reasons for the problems above are presence of dielectric stress, circulating currents, voltage transients, high$\frac{dv}{dt}$, common mode voltage and switching frequency. Semi conductor Technology has advanced to levels where 600V can be switched for from on to off within milli seconds which in turn causes electromagnetic inference (EMI)[1].

The broad classification of modulation strategies for control of variable speed drives are low switching frequency and high switching frequency. The high frequency switching techniques as space vector pulse width modulation technique and carrier based pulse width modulation techniques can cause the following phenomenon.

- Increased thermal loss reducing system efficiency
- Damage of motor bearing & Insulation due high $\frac{dv}{dt}$
- Side Bands of carrier in power of order 10-30KHZ causes electromagnetic interference
- Ripples in voltage & current wave forms.

Instead, low switching frequency modulation techniques such as selective harmonic elimination (SHE) has inherent advantages such as low switching losses, control over output voltages harmonics and good harmonics profile [2]. SHE Technique suffers from the drawbacks of solving non linear transcendental SHE equations to provide a feasible solution at a particular modulation index to produce low %THD to comply with IEEE 519-1992 harmonic guidelines. This topic has attracted researches in past few decades and in recent times is use of various soft computing techniques for solving SHE equations to get better solution with less computational effort and time. In literature several techniques have been proposed such as Newton Raphson Method, WALSH , Resultant theory, theory of systematic polynomials, all these techniques suffers long computational time, tedious calculations and unable to provide feasible solutions during complete range of modulation index from 0 to 1[3]-[5]. Stochastic optimisation techniques like, genetic algorithm, modified species based optimisation technique and fire fly algorithms are used to provide the feasible solutions for SHE equation set. All these optimisation techniques require initialization parameters such as mutation rate, social parameter, cognitive parameter, constriction factor etc[6]-[8].

Recently, a novel learning based Optimization Technique algorithm was proposed by Rao et.al., aimed to solve machine design problems which is effective, robous t and compact in terms of coding compared to bio inspired algorithms[9]. This paper compares the effectiveness of TBLO algorithm to that of conventional NR method in solving SHE equations set which are formed in control of three phase CHB 7-level inverter.

2. SHE Technique and Problem Formation

The selective harmonic elimination method is also known as fundamental switching frequency method based on the harmonic elimination theory. It is a modulation strategy whose goal is to determine the proper switching angles to eliminate specific harmonics especially lower harmonics which cause to minimize the output waveform THD. SHE technique has several features such as direct control over the output voltage harmonics, low switching frequency modulation technique which results in low switching losses and also the ability to leave triple harmonics which is the multiple of third order harmonics. SHE method can also called as programmed PWM method and has been widely used in applications such as improvement of power quality, proper functioning of MV drives, also HVDC systems and distribution phenomenon.

High switching frequency modulation techniques like carrier based PWM techniques and space vector modulation techniques produces side bands around carrier frequency which results in high %THD. However, in control of multilevel inverter operating at above 1MW power level, device switching frequency above 500 Hz will results in high switching losses and thermal losses. Hence, low switching frequency technique such as selective harmonic elimination technique is one of the preferred techniques at MW power levels. However, providing the feasible solutions (switching angles) for the non linear transcendental SHE set is a challenging task for the researchers over decades. As voltage levels increases, the number of variables to be found in SHE equations set also increases, thus the computing burden also increases[10].

One of the preferred topology in variable speed applications is three phase CHB 7-level to 11-level inverter. Hence, three phase CHB 7-level inverter is chosen for analysis. Fig.1 shows the circuit configurations of a three phase cascaded H-bridge inverter and while Fig.2 presents the per phase output voltage waveform for a seven level inverter with its switching pattern. Applying Fourier series for the staircase output voltage waveform of CHB 7 level inverter, as shown in Fig.1, it is given by

$$V_{an}(\omega t) = \sum_{k=1,3,5..}^{\infty} \frac{4v_{dc}}{k\pi}(\cos(k\alpha_1).....+\cos(k\alpha_s))\sin(k\omega t) \quad (2)$$

Where‘s’ is a number of H bridges connected in cascade per phase. Here, three single phase H-bridges are connected per phase and cascaded with each other. V_{DC} is input voltage of each H -bridge and total output voltage in each phase is given by:

$$V_{RN} = V_{H1} + V_{H2} + V_{H3} \quad (3)$$

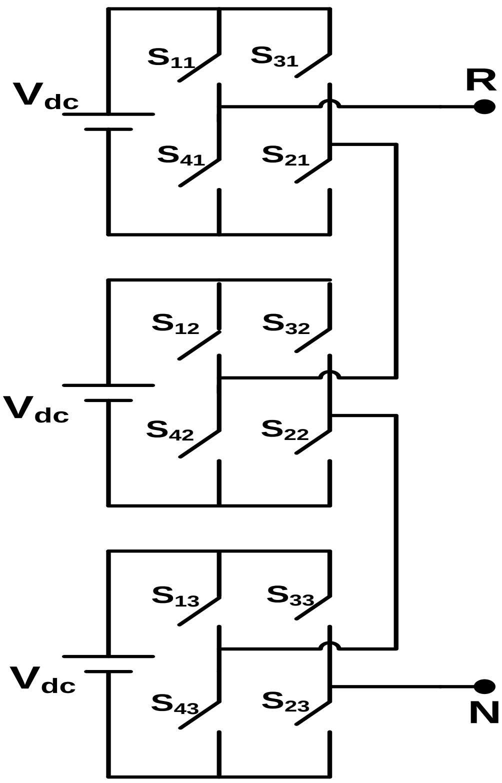

Fig. 1. Single phase CHB 7-level inverter

In SHE technique the constraint of the switching angles is considered in between 0^o and 90^o ($0\leq\alpha\leq90^o$). According to Fourier series, when the square wave gets decomposed into their Fourier sine wave components, it will not have even harmonics because of symmetry and the tripled harmonics can be eliminated by adjusting modulation index to multiples of three. Considerably the fundamental output voltage (V_1) in terms of switching angles can be given as:

$$\frac{4v_{dc}}{\pi}(\cos(\alpha_1)+\cos(\alpha_2)+.....\cos(\alpha_s))=V_1 \tag{4}$$

M_I is defined as the ratio of fundamental output voltage (V_1) to maximum obtainable fundamental voltage V1max .V1max can be achieved by making all switching angles to zero degrees.

$$V_{1\max}=4sV_{dc}/\pi \tag{5}$$

M_I can be expressed as:

$$M_I=\pi V_1/4sV_{dc}(0\le M_I\le 1) \tag{6}$$

Since there are three H-bridges per phase for a CHB 7-level inverter it consists with three degrees of freedom. Among those three degrees of freedom, one degree of freedom is to produce fundamental voltage and remaining two degrees are used to eliminate lower order harmonics i.e., 5^{th} and 7^{th}. The modulation methods used in multilevel inverters can be classified according to switching frequency. The main aim is to attain the maximum fundamental voltage with minimization in lower order harmonic content. So with the Combination of equations (1) and (5), SHE equations can be presented as

$$\begin{aligned}&[\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)]/3=M_I\\&\cos(5\alpha_1)+\cos(5\alpha_2)+\cos(5\alpha_3)=0\\&\cos(7\alpha_1)+\cos(7\alpha_2)+\cos(7\alpha_3)=0\end{aligned} \tag{7}$$

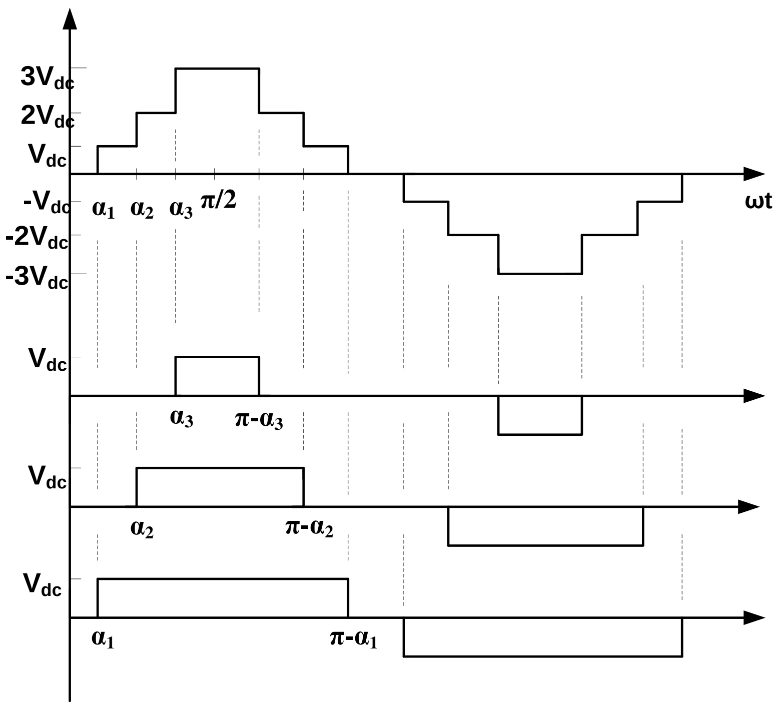

Fig. 2. Per phase Voltage waveform of CHB 7-level inverter representing seven steps in output volatge.

Cost function

Fitness function or cost function is formed by adding original objective function to penalty factor. The fitness value is a measure of the exactness of a solution with respect to the original objective. Here, the main aim is to get a set of switching angles so that the magnitude of fundamental harmonic reaches a desired value. For each solution the fitness function is calculated as follows [6].

$$f = \min_{\alpha_i}\left\{100\left(\frac{V_1^* - V_1}{V_1^*}\right)^4 + \sum_{n=2}^{s}\frac{1}{h_n}\left(50\frac{V_{h_n}}{V_1}\right)^2\right\}; \tag{8}$$

$$=1, 2,.................s \text{ Subject to: } 0 \le \alpha_i \le \pi/2 \tag{9}$$

3. Newton-Raphson Method

NR method is one of the widely used and well established technique to solve non linear equations .H. S. Patel & R. G. Hoft in 1973[11], first applied NR method to solve SHE equations to obtain feasible switching angles to eliminate harmonics. Though, this technique is extremely powerful one, it suffers from the drawback of requirement of good initial guess. Since the search space is unknown, providing good initial guess is so complex. Hence, in order to overcome the above mentioned drawback, an approach of "any random initial guess" has been considered for developing algorithm [12].

The steps involved in development of the algorithm are

Step 1: Assume any random Initial Guess (Say α_0)

Step 2: Set $M_1 = 0$

Step 3: Calculate F(α_0)),B(M_1) and Jacobian matrix J(α_0))

Step 4: Calculate error $\Delta\alpha = \alpha_0 \left[\frac{\partial F}{\partial \alpha}\right]^{-1} \left[B[M_1] - F[\alpha_0]\right]$

Step 5: Update the switching angles i.e $\alpha(n+1) = \alpha(k) + \Delta\alpha(n)$

Step 6: Repeat the steps (3) to (5) for sufficient number of iterations to attain error goal.

Step 7: Increment M_1 by a fixed step

Step 9: Repeat steps (2) to (7) for complete range of M_1.

The proposed algorithm is developed on MATLAB programming environment and the effectiveness of proposed algorithm is tested in solving non linear transcendental SHE equation set.

4. Teaching Learning Based Optimisation Technique

TLBO is a teaching-learning based optimization algorithm based on the effect of influence of a teacher on the learner's output within a class. The main component of this algorithm is teacher and learners. The teacher describes two basic modes of the learning (known as teacher phase) and interaction with the other learners within the class (known as learner phase). This optimization algorithm consist a group of learners that are considered as population and different design variables are considered as different subjects. Among entire population the best solution is teacher. The output of the TLBO algorithm is considered among the terms of results or grades of the learners that literally depends on the quality of teacher. Here highly learned person is the teacher who trains the learners to get better results among the categories of their marks or grades. Moreover, learners gets an opportunity to learn a lot from the interactions among themselves so, it helps with the improvement of their results or grades [9].

The algorithm describes two basic modes of the learning:

(i) Through teacher (known as teacher phase) and

(ii) Interacting with the other learners (known as learner phase).

Implementation of TLBO algorithm for optimization is as follows:

Define the optimization problem and initialize the optimization parameters.

Initialize population size (P_n), number of generations (G_n), number of design variables (D_n) and limits of design variables (U_L , L_L).

Generate a random population according to the population size and number of design variables. For TLBO, the population size indicates the number of learners and the design variables indicates the subjects offered. This population is expressed as follows:

$$\text{Population}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1D} \\ x_{21} & x_{22} & \cdots & x_{2D} \\ \cdots & \cdots & \cdots & \cdots \\ x_{P_n,1} & x_{P_n,2} & \cdots & x_{P_n,D} \end{bmatrix} \tag{10}$$

Teacher phase:

Calculate the mean of population column-wise, which will give the mean for the particular subject as

$$M_{*,D} = [m_1, m_2, ..., m_D]. \tag{11}$$

The best solution will be act as a teacher for that iteration

$$X_{teacher} = X_{f(X)=\min} \tag{12}$$

The teacher will try to shift the mean from $M_{*,D}$ towards $X_{*,teacher}$ which will act as a new mean for the iteration. The difference between two means is expressed as

$$Difference_{*,D} = r(M_{new,D} - T_F \times M_{*,D}), \tag{13}$$

where the value of T_F is selected as 1 or 2. The obtained difference is added to the current solution to update its values using

$$X_{new,D} = X_{old,D} + Difference_{*,D} \tag{14}$$

Accept X_{new} if it gives better function value.

Learners phase:

Learners increase their knowledge with the help of their mutual interaction. The mathematical expression is as follows:

$$\begin{cases} X_{new,i} = X_{old,i} + r_i(X_i - X_j) \\ X_{new,i} = X_{old,i} + r_i(X_j - X_i) \end{cases} \tag{15}$$

Termination criteria stop if the maximum generation is achieved; otherwise repeat from Teacher phase.

5. Simulation Results and Discussions

The proposed techniques like NR method and TLBO algorithms are used to solve non linear transcendental SHE equations set which are formed in control of three phase CHB 7-level inverter and comparative analysis have been carried out. The MATLAB programming environment has been considered to developed the code for the proposed techniques and SIMULINK model is also developed to observe %THD & FFT analysis.

5.1 Newton Raphson method

The proposed algorithm is developed in MATLAB programming environment and run from modulation index of value from 0.5 to 1 in steps of 0.05. The feasible switching angles say α_1, α_2 and α_3 which produce less %THD at each value of modulation index are tabulated in Table I. Fig. 3 represents switching angles α_1, α_2 and α_3 at various values of modulation index. It is observed that there is no solution for SHE equations set below the value 0.4 and above the value of 0.8. Multiple solutions are attained during the range of 0.5 to 0.62 M_I. Single solution is obtained during the range of 0.4 to 0.49 M_I and from 0.63 to 0.79 M_I. The phase voltage waveform of CHB 7-level inerter which represents seven steps of output voltage is represented in Fig. 4 and line to line voltage waveform is represented in Fig. 5 respetively. Average computational time required to run the algorithm at selected values of modulation indices are 07.00 sec only. It is also observed the proposed NR method could not provide the feasible solution at the modulation indices of values 0.85, 0.9, 0.95 and 1.0.

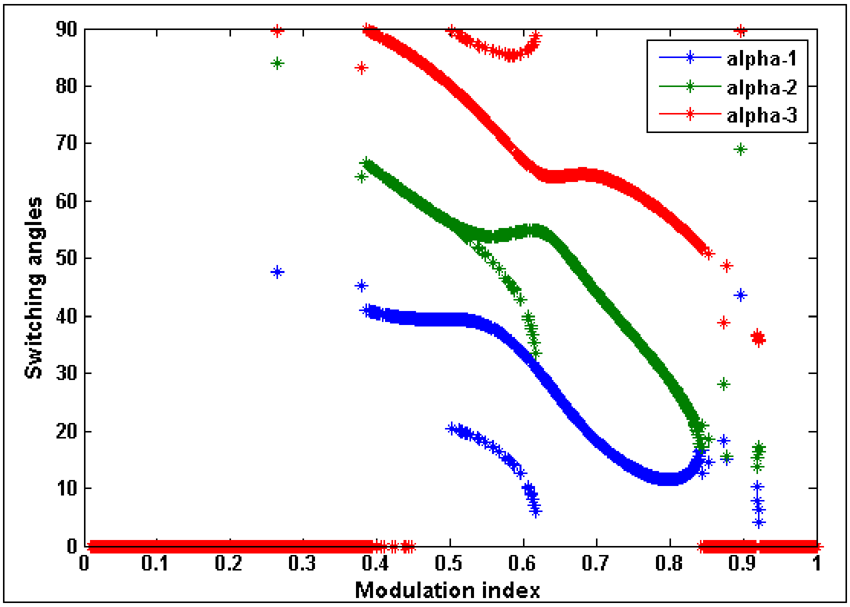

Fig. 3. Switching angles Vs Modulation Index

Table 1. Switching angles in degrees & %THD

S.No	M_I	α_1	α_2	α_3	%THD
1	0.5	39.42	56.25	80.09	13.07
2	0.55	17.9	50.39	86.50	17.31
3	0.6	11.82	41.71	85.75	13.26
4	0.65	25.62	52.12	64.25	10.57
5	0.7	18.30	44.11	64.36	12.29
6	0.75	13.52	36.61	61.63	9.02
7	**0.8**	**11.50**	**28.71**	**57.10**	**8.86**
8	0.85	**No solution**			
9	0.9	**No solution**			
10	0.95	**No solution**			
11	1	**No solution**			

From Table I, it is observed that %THD value gradually decreases as the modulation index increases and minimum %THD of value 8.86% has obtained at a modulation index of value 0.8. FFT analysis at the value of value of 0.8 M_I is shown in Fig. 6, it is observed that the targeted order of harmonics say 5th and 7th are minimized to that greater extant. The magnitudes of harmonic voltages are below 5%. The %THD produced has complies with IEEE 519-1992 harmonic guidelines too. The %THDs obtained at the values of modulation index below 0.8 are high and needs an additional filters to bring the values nearer to IEEE 519-1992 harmonic guidelines too.

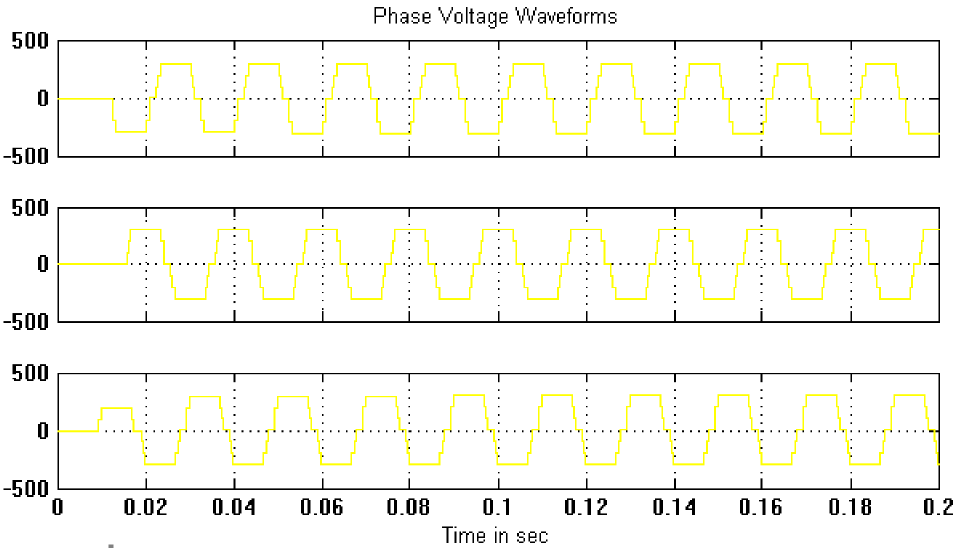

Fig. 4. Phase voltage waveform of three phase CHB 7-level inverter.

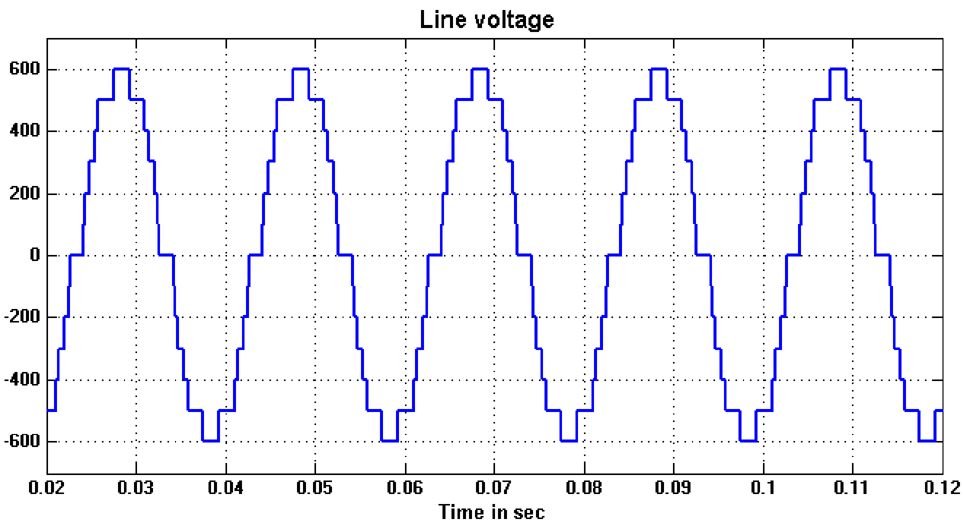

Fig. 5. Line to line output volatge of three phase CHB 7-level inverter

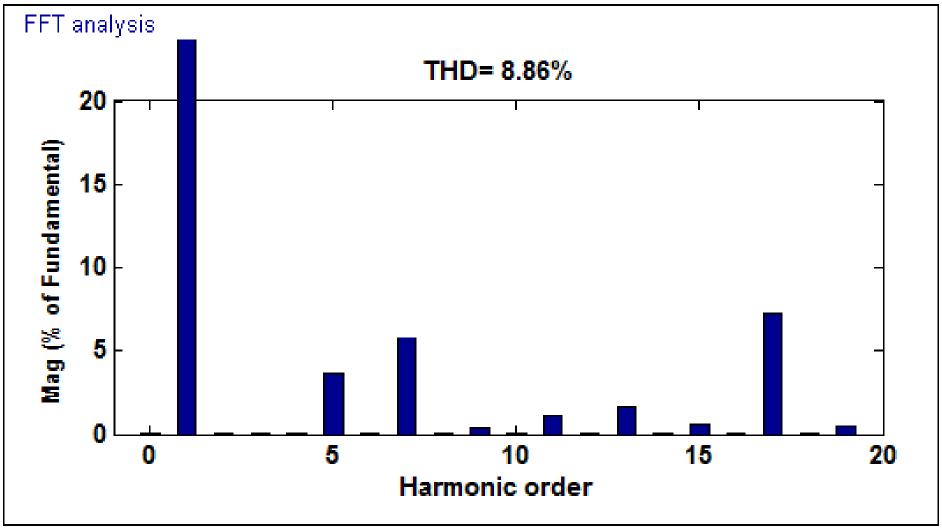

Fig. 6. FFT analysis representing harmonic order at the M_I of value 0.8.

5.2 *Teaching Learning based Optimization Technique:*

The code for Proposed TLBO algorithm is developed in MATLAB programming environment and the program is run at different modulation indices from 0.5 to 1.0 in steps of 0.5 and at each step the obtained switching angles of SHE equation set and %THDs are tabulated in Table 2. The values of %THD obtained at different steps of modulation indices are decreased gradually as the modulation index is increased.

Table 2 Switching angles in degrees and %THD

S.No	M_i	α_1	α_2	α_3	%THD
1	0.5	21.59	54.81	84.09	19.42
2	0.55	18.36	47.50	85.06	17.85
3	0.6	19.18	43.70	84.95	18.37
4	0.65	17.33	30.61	85.37	18.28
5	0.7	15.26	37.35	72.70	15.27
6	0.75	1.96	36.13	63.48	15.8
7	0.8	9.38	13.56	39.18	12.5
8	0.85	4.02	37.07	45.8	12.19
9	0.9	6.5	13.25	43.62	10.98
10	0.95	2.70	16.2	32.25	6.95
11	1	5.23	7.05	30.98	7.30

The value of %THD obtained at the modulation index of value 0.95 is 6.95% and completely complies with IEEE 519-1992 harmonic guidelines too. FFT analysis at 0.95 modulation index is shown in Fig. 7. It is observed that all targeted order of harmonics are minimized and below 5% in magnitude only. It is further observed that the average computational time required for running the TLBO code is 16.6 sec. The potential of TLBO algorithm is, it has successfully solved SHE equation set at the modulation indices of value 0.85,0.9, 0.95 and 1.0.

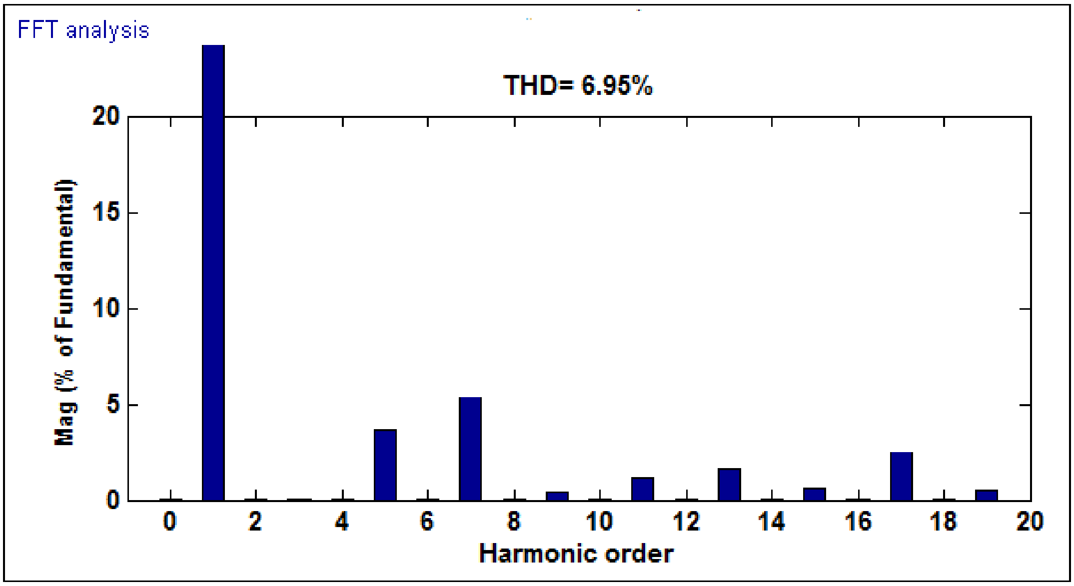

Fig. 7. FFT analysis representing harmonic order at the M_I of value 0.95.

Comparative analysis of %THD at different values of modulation indices are shown in Fig. 8. It is observed that though the %THDs obtained by NR method is minimum but it could not provide the feasible solutions at the modulation index of values 0.85 and above. The TLBO algorithm has successfully solved the SHE equation set where NR method could not solve it. The TLBO algorithm has solved the SHE equation set at highest magnitude of the fundamental voltage with minimum %THD of value 6.95%. The computational time required for both the algorithms are less but NR method is still less with the average value of 07 sec.

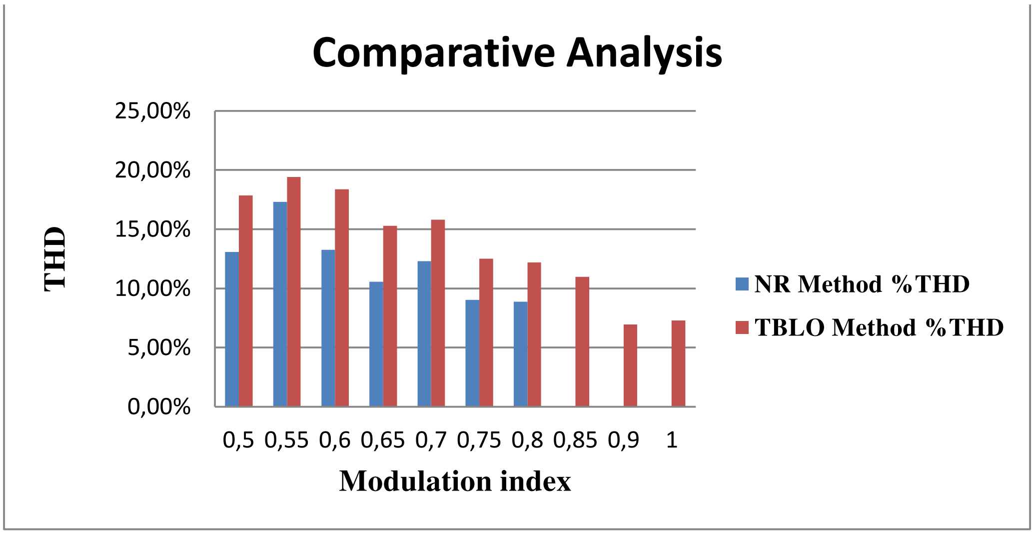

Fig. 8. Comparative analysis of %THDs at different modulation NR method and TLBO method

Conclusions

This paper mainly focused on comparative analysis of various algorithms to solve non linear transcendental SHE equations set to obtain the feasible switching angles in control three phase CHB 7-level inverter. It is observed that TLBO algorithm is rugged, efficient and with less computational effort it has solved SHE equation set form 0.5 to 1.0 values of modulation index where NR method could not provide the feasible solution at the values of modulation indices 0.85, 0.9, 0.95 and 1.0. Though, the %THDs obtained by TLBO algorithm is high at different values of M_I are high but at 1.0 M_I the %THD obtained by TLBO algorithm is less in value say 6.95% which complies with IEEE 519-1992 harmonic guidelines too. The computational time for NR method is very less say 07 sec but it has a problem of struck at global minima. The TLBO algorithm takes somewhat more computational time say 17 sec but it can find feasible solutions at different values of M_I where NR method could not find. However, it is observed that, TLBO algorithm needs several runs to find the near global values for this optimization problem. Future research may focus on working on Elitist TLBO optimization and some other optimisation techniques to overcome the above problem [14].

References

1. J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," IEEE Transaction on Industrial electronics, vol. 49, no. 4, pp. 724–738, Aug. 2002.
2. J. Napoles, A. J. Watson, J. J. Padilla, J. I. Leon, L. G. Franquelo, P. W. Wheeler and M. A. Aguirre, "Selective Harmonic Mitigation Technique for Cascaded H-Bridge Converters with Non-Equal DC Link Voltages", IEEE Transactions on power electronics, pp. 1-9, 2012.
3. John N. Chiasson, Leon M. Tolbert, Keith J. McKenzie and Zhong Du, "A Complete solution to the harmonic elimination problem", IEEE transactions on power electronics, vol. 19, no. 2, pp. 491-498,March 2004.
4. J.Sun and H.Grotstollen, "Solving Nonlinear equations for Selective harmonic eliminated PWM using predicted initial values," in Proc.Int.Conf.Industrial Electronics, Control, Instrumentation, Automation, 1992, pp. 259-264
5. J.Chiasson, L. Tolbert, K. McKenZie, and Z. Du, "Eliminating harmonics in a multi-level converter using resultant theory of symmetric polynomials and resultants," IEEE trans. Control Syst. Technol., Vol.13,No 2, pp. 216-223, Mar. 2005
6. Reza S, Naeem F, Mehrdad A and Syed Hamid F, " Elimination of Low order harmonics in Multilevel Inverter using Genetic Algorithm," Journal of Power Electron, vol. 11, no. 2, pp. 132–139, 2011.
7. Ozpineci B, Tolbert LM and Chiasson JN, " Harmonic Optimization of Multilevel Converters Using Genetic Algorithms," IEEE Power Electron Lett, vol. 3, no. 3, pp. 92–95, 2005
8. Tarafdar M, Taghizadeh H and Razi K, "Harmonic Minimization in Multilevel Inverters Using Modified Species- Based Particle Swarm Optimization," IEEE Trans Power Electron , vol.24, no. 10, pp. 2259–2266, 2009.
9. Venkata Rao R and Vivek P, " A teaching-learning based optimization algorithm for solving complex constrained optimization problems", Int J Ind Eng Comput, vol. 3, pp. 535-560, 2012 .
10. Samir Kouro, S. La Rocca, B. Cortes, P. Alepuz, S. Bin Wu Rodriguez, J. "Predictive control based selective harmonic elimination with low switching frequency for multilevel converters" Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE, pp- 3130 – 3136.
11. H. S. Patel and R. G. Hoft, "Generalized harmonic elimination and voltage control in thyristor inverters: Part I—Harmonic elimination,"IEEE Trans.Ind. Appl., vol. IA-9, no. 3, pp. 310–317, May/Jun. 1973.
12. Jagdish Kumar, Biswarup Das and Pramod Agarwal, "Selective harmonic elimination technique for a multilevel inverter", Fifteenth National power Systems Conference (NPSC), IIT Bombay, December 2008.
13. Venkata Rao R and Vivek P, "An elitist teaching-learning based optimization algorithm for solving complex constrained optimization problems," Int. J Ind Eng Comput., vol. 3, pp. 535–560, 2012.