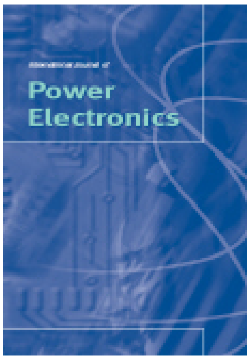

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Optimum regulation of THD profile in multilevel inverter using parameter-less AI technique for electrical vehicle application

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Abstract: This article proposes investigation on harmonic profile improvement using a novel fitness function in the multiphase multilevel inverter. For the proposed study in this paper, three-phase, seven-level cascaded H-bridge (CHB) multilevel inverter (MLI) is considered. Modulation of the stepped waveform output of the MLI is done using selective harmonic elimination (SHE) method. Many algorithms are proposed for solving the set of nonlinear transcendental trigonometric equations for SHE methods. Teaching learning-based optimisation (TLBO) algorithm is a parameter less optimisation technique. Due to the lack of controlling parameters, the proposed algorithm is most robust among the family of artificial intelligence (AI) techniques. In this paper, an investigation is carried out on a novel fitness function proposed for controlling total harmonic distortion (THD) for the proposed inverter. It is observed that the proposed fitness function improves THD profile below IEEE standards. It is also observed that THD profile obtained through this method is far better than THD profile obtained through various proposed methods so far. The results of THD profile from the MATLAB Simulink simulations are verified experimentally using seven-level three-phase hardware controlled by Arduino MEGA 2560 low-cost controller.

Keywords: multilevel inverter; artificial intelligent algorithm; teaching learning-based optimisation technique; selective harmonic elimination; SHE; total harmonic distortion; THD.

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1 Introduction

Low-cost hybrid electrical vehicles (HEV) and electric vehicles (EVs) have attracted researchers in developing countries. Many of the research include three-phase induction motors for low-cost requirements, owing to their low-cost of production and almost null requirement of maintenance in case of squirrel cage induction motor. The maturity of power electronic (PE) drives has increased to the extent that they can contribute to the fresh idea of producing low-cost electrical vehicles. The main requirement of any PE drive for an EV is low total harmonic distortion (THD), modular structure, no electromagnetic interference, and less space requirement. A cascaded H-bridge multilevel inverter (CHB-MLI) is seen to be the best candidate for PEs drive in low-cost EV and HEV applications. CHB-MLI has advantages of modular structure. CHB-MLI pose null electromagnetic interference when SHE-based THD reduction is used. It uses very less space due to lack of power diodes and bulky power capacitors, as in the case of diode clamped and capacitor clamped multilevel inverters (Sabahi et al., 2011; Malarvizhi and Gnanambal, 2015b, 2015a). CHB-MLI is also most suitable to the HEV, and EV application, as from the battery bank or set of fuel cells each battery or fuel cell can feed one of the H-bridge in cascaded connection (Tolbert et al., 1998; Dhayanandh et al., 2011; Ebadpour et al., 2011).

The life span of the induction machine can be saved from excessive heating and harmonic torques if THD is reduced below IEEE standards (Committee et al., 2014). CHB-MLI produces a stepped waveform of the output voltage, which contains harmonics. THD from the output voltage can be reduced to an optimum level with the help of various THD minimisation techniques, i.e., fitness functions and optimisation algorithms. Many researchers have taken a keen interest in developing machine code for such an AI technique and minimised the THD at the output of the CHB-MLI.

In Manohar et al. (2016), a seven-level three-phase CHB-MLI is studied using a comparative analysis of the NR and TLBO method. In this study, the proposed fitness function gives THD of 6.95% in line voltage. In Kumar and Thangavelusamy (2019), a modified nearest level scheme is used for THD minimisation, which gives minimum THD to be 10.6% in line voltage. In Jannati-Oskuee (2017), researchers used a seven-level three-phase inverter and optimised harmonics directly online voltage with alterable DC sources. The THD obtained through this study is 5.95%. In Fathi and Bakhshizadeh (2012) used GA-based minimisation of THD directly online voltage with variable DC sources and obtained a THD level of 6.1%. In Fathi et al. (2009), researchers applied THD minimisation directly on Phase voltage using the homotopy algorithm of three-phase seven-level inverter. The THD obtained by this study is 6.78% in line voltage. In Khamooshi and Moghani (2014), authors have used the BAT algorithm for seven-level, three-phase CHB-MLI with alterable DC sources for THD minimisation. The authors have directly applied THD minimisation on phase voltage. THD obtained by this study is 13.27% in phase voltage. In Khamooshi and Namadmalan (2016), a switch utilisation ration scheme is used for THD minimisation in five-level, seven-level, nine-level, and 11-level, three-phase CHB-MLI. Authors achieve a THD of 6.23% in line voltages using their proposed method in seven-level CHB-MLI. In Mardaneh and Golestaneh (2013) used THD reduction on phase voltage and obtained a THD value of 8.1% in line voltage of a seven-level inverter. In Olamaei and Karimi (2018), authors have worked on seven-level CHB-MLI using a fitness function derived from the fundamental equation of phase voltage THD. Researchers could achieve a line voltage THD of 10.33%.

In this paper, a fitness function is derived using the concept of selective harmonic elimination. The fitness function is optimised using a parameter less TLBO algorithm. THD obtained in this study is the lowest among all literature using a seven-level three-phase CHB-MLI.

The rest of the research article is organised as follows. Section 2 presents a brief discussion on three-phase seven-level CHB-MLI, the formation of proposed fitness function based on the SHE PWM technique. Section 3 introduces the TLBO algorithm. Section 4 presents results and discussion, and a comparison of the result of the proposed method with other researches is tabulated. Section 5 presents the conclusions of the study, followed by references.

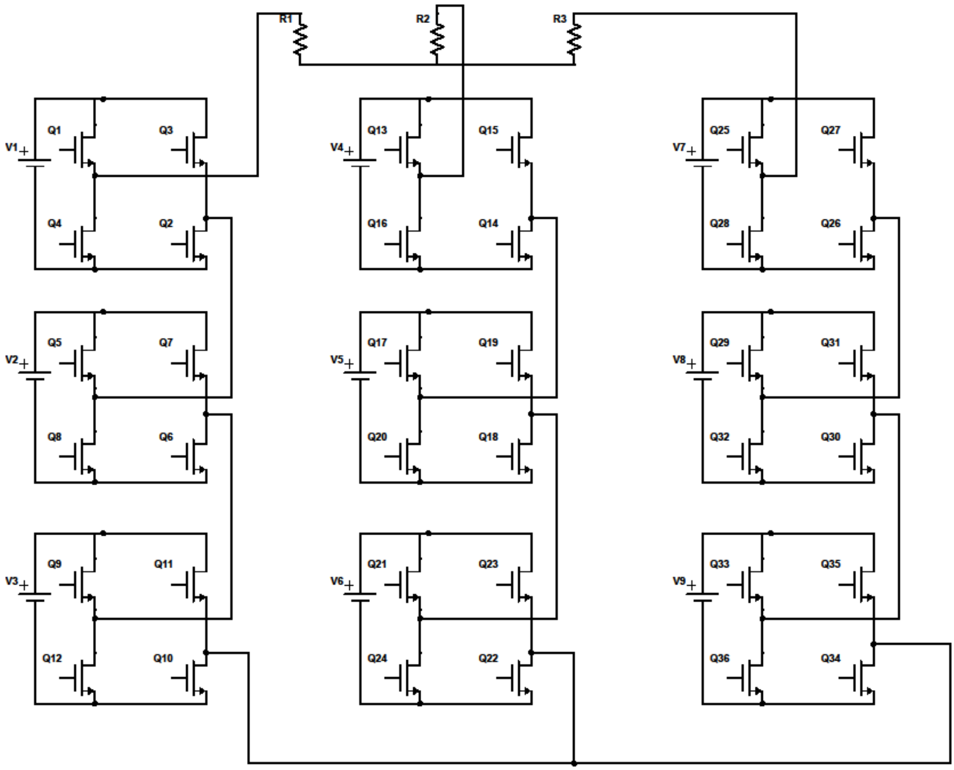
2 CHB-MLI, SHE method and formation of fitness function

2.1 Three-phase seven-level CHB-MLI

CHB-MLI is a series connection of N number of H-bridge inverters, as shown in Figure 1. Each inverter module produces a quasi square wave at the output and a stepped waveform is synthesised at the output terminals, as shown in Figure 2. The number of levels at the output is determined from the equation $L = 2M + 1$, where M is number of H-bridges or number of individual power sources. A seven-level three-phase inverter is shown in Figure 1, and the seven-level stepped output waveform is shown in Figure 2 (Ozpineci et al., 2005; Etesami et al., 2011).

In Figure 1, there are three legs, and each leg contains three H-bridges, so there are ($2 \times 3 + 1 = 7$) seven-level produced at the output per phase voltage waveform. A three-phase connection is produced by star connection of all three-phase or limbs. All the loading elements are considered to be balanced in this study.

Figure 1 Three-phase seven-level CHB-MLI



2.2 Fourier representation of the output stepped waveform

The waveform shown in Figure 2 is represented mathematically by the Fourier transform equations. Equation (1) gives the mathematical representation of the output waveform using the Fourier transform.

$$v(wt) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(nwt) + b_n \sin(nwt)] \tag{1}$$

Under the balanced loading condition, the waveform shown in Figure 2 is considered as quarter-wave symmetrical. The DC component of equation (1) that is a_0, cosine components' odd and even terms and even terms of sine component, are zero. The modified equation, in this case, is given in equation (2). Equation (3) gives the value of the component b_n.

$$v(wt) = + \sum_{n=1,3,5,\ldots}^{\infty} b_n \sin(nwt) \tag{2}$$

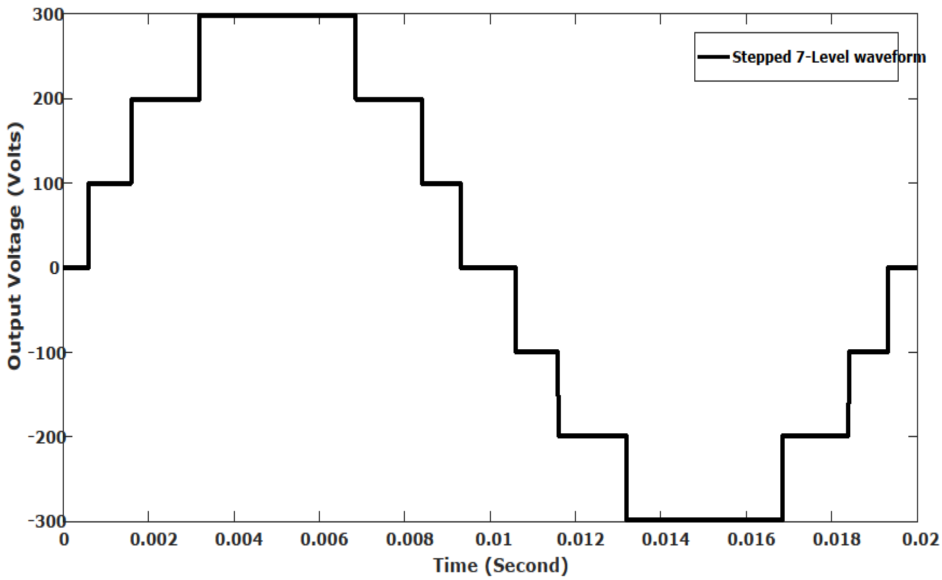
$$b_n = \frac{4V_{DC}}{n\pi} \left[\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3) \right] \tag{3}$$

The final equation of the output voltage after removing all the zero components is given in equation (4) (Yazdani et al., 2013).

$$v(wt) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{DC}}{n\pi}\left[\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)\right]\sin(nwt) \tag{4}$$

It should be noted at this instance that equations (1) to (4) belongs to a seven-level inverter. For the higher-level inverter, modification is required accordingly. It should also be noted that in the three-phase system, all triplen harmonics are zero owing to its three-phase structure and 120-degree phase difference.

Figure 2 One-phase seven-level synthesised waveform at the output of CHB-MLI



2.3 Selective harmonic elimination-based THD minimisation and formation of the fitness function

In CHB-MLI, when particular harmonics are selected for elimination from the output voltage, that is called selective harmonic elimination. When higher-order harmonics are targeted for elimination, THD is reduced in the three-phase system, which is again added by the loss of triplen harmonics in the three-phase system. Selective harmonic elimination-based THD minimisation has many advantages over other methods of harmonic reduction, such as high power quality, small filter size, low electromagnetic interference due to the fundamental frequency of modulation, pre-calculated angles can be stored for online applications (Bhatt and Chakravorty, 2020a, 2020b).

A set of nonlinear transcendental equations can be formulated from equations (1) to (4) as given by equations (5) to (8) below,

$$\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = 3M \tag{5}$$

$$\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0 \tag{6}$$

$$\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) = 0 \tag{7}$$

$$\cos(11\alpha_1) + \cos(11\alpha_2) + \cos(11\alpha_3) = 0 \tag{8}$$

where

M modulation index

α_1, α_2, α_3 firing angles for each step in seven-level inverter.

From equations (5) to (8), many researchers have introduced various fitness functions, which are then optimised by various AI techniques. The result of the optimisation code is the firing angles for the PE switches used in CHB-MLI. In this research paper, a fitness function is derived using the SHE pulse width modulated THD minimisation scheme.

2.4 Formulation of fitness function

A novel fitness function is proposed in this paper. The proposed fitness function uses equations (5) to (8). Equations (9) to 12 shows formation of fundamental component and higher-order harmonics. The formulation of the proposed fitness function is given equation (14).

$$h_1 = \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) \tag{9}$$

$$h_5 = \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) \tag{10}$$

$$h_7 = \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) \tag{11}$$

$$h_{11} = \cos(11\alpha_1) + \cos(11\alpha_2) + \cos(11\alpha_3) \tag{12}$$

Here h_1 indicates fundamental component, h_5, h_7 and h_{11} represents 5th, 7th and 11th level harmonics. Each higher-order harmonic is divided by its order, as given in equation (13).

$$THD = \sqrt{\left(\frac{h_5}{5}\right)^2 + \left(\frac{h_7}{7}\right)^2 + \left(\frac{h_{11}}{11}\right)^2} \tag{13}$$

Equation (13) represents the formation of THD equation. Here three higher-order harmonics, namely 5th, 7th, and 11th order harmonics, are considered. Here triplen harmonics such as 3rd and 9th harmonics are not considered because triplen harmonics are naturally eliminated in the three-phase structure of CHB-MLI.

$$\text{Proposed fitness function} = \left(10 \times |h_1 - 3M|\right) + (THD / 10) \tag{14}$$

where

M modulation index.

$$M = \frac{V_1}{\left(\frac{12V_{DC}}{\pi}\right)} \tag{15}$$

h_1 = fundamental component

Equation (14) gives the final formation of the fitness function. In this fitness function, the fundamental part is multiplied by a factor of 10 to increase the weightage of fundamental voltage magnitude with respect to harmonics. The THD part is divided by a factor of 10 to suppress the higher-order harmonics and make the optimisation process smooth, intern that helps the algorithm reach the global optima.

The first term (h_1 – 3M) in the right side of equation (14) is obtained from equation (5) and equation (9). The left side of equation (5) represents fundamental component which is represented in equation (9) and the right side of equation (5) is three times modulation index (3M). Equating equation (5) and equation (9), the term $h_1 - 3M$ is obtained in equation (14). Moreover the term 3M in equation (5) is derived in Appendix after the reference section.

Among many of the references discussed in the introduction section proposed fitness function, when applied only to the phase voltage, gives the lowest value of THD in line voltage when optimised with the TLBO algorithm. The following section discusses the TLBO algorithm before discussing the results.

3 Teaching learning-based optimisation algorithm

The teaching learning-based optimisation algorithm is proposed by Rao and Patel (2013). The algorithm is popular among researchers due to its parameter less property and robust nature. TLBO works in two parts, namely the teacher part and the learner part. A class of students is created under each variable classroom as a subject. The most knowledgeable student in the class acts as a teacher. Other students come to the teacher for the improvement of knowledge. Thus each student in a classroom represents a possible candidate solution for the subject or variable defined. After the final iteration, the most knowledgeable student gives the optimum global result of the fitness function. Procedural steps for the teacher and students phase in explained in the following sub-sections.

3.1 Teacher phase

In the teacher phase, the teacher tries to improve the knowledge of the whole classroom, i.e., subject design variable. The mean of the students' knowledge is found for each design variable. Equation (16) represents the knowledge transfer process from the teacher to the learner.

$$\alpha_{new,i}^{k} = \alpha_i^k + r\left(Th^k - M^{k-1}\right) \tag{16}$$

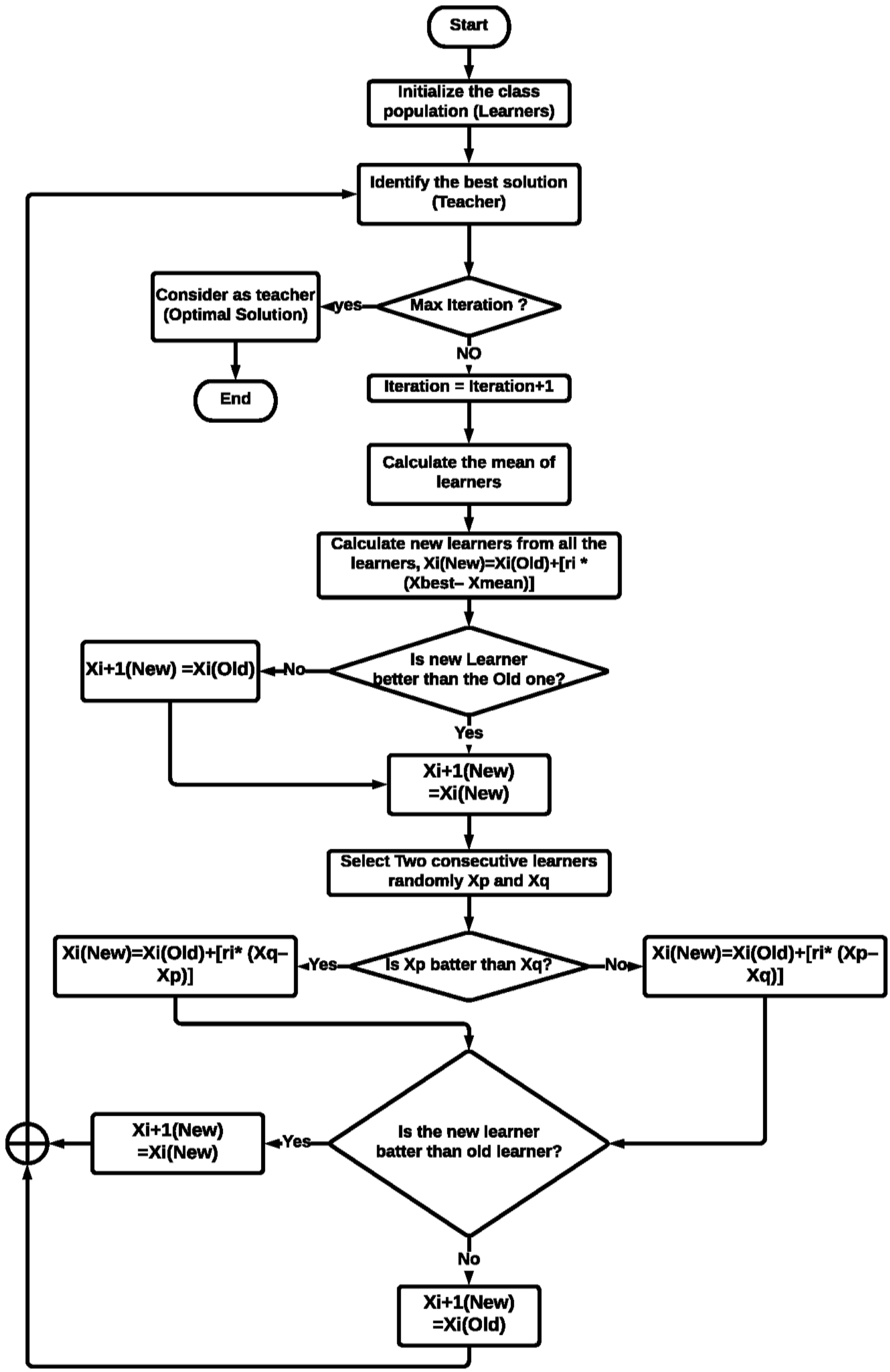
where

α_i^k switching angle vector of the i^{th} student in iteration k

Th^k the best switching angle vector acts as a teacher

$\alpha_{new,i}^{k}$ new switching angle vector after the teaching process, it only gets accepted if it is better than the previous value.

Figure 3 Algorithm flowchart for teacher learner-based optimisation technique



3.2 Learner phase

After the teaching phase, the learning phase starts. A teacher tries to impart knowledge to all the students in the class, but the grasping level of individual students is different. In the learning phase, students interact with each other randomly to share and seek knowledge, respectively. The knowledge transfer takes place from knowledgeable students to the knowledge-seeking student. The knowledge transfer process is expressed by equation (17) or equation (18).

Randomly two students interact for knowledge transfer, say α_x^k, and α_y^k in the kth iteration.

If $F(\alpha_x^k) > F(\alpha_y^k)$, i.e., α_x^k is more knowledgeable. Equation (17) transfers the knowledge, from knowledgeable students to the knowledge-seeking student.

$$\alpha_{new,i}^k = \alpha_i^k + r\left(\alpha_x^k - \alpha_y^k\right) \tag{17}$$

If $F(\alpha_y^k) > F(\alpha_x^k)$, i.e., α_y^k is more knowledgeable. Equation (18) transfers the knowledge, from knowledgeable students to the knowledge-seeking student.

$$\alpha_{new,i}^k = \alpha_i^k + r\left(\alpha_y^k - \alpha_x^k\right) \tag{18}$$

Steps for implementation of MATLAB code for the TLBO algorithm can be derived from the flowchart given in Figure 3.

4 Results and discussion

In this section proposed fitness function discussed in the previous section is optimised using the TLBO algorithm. For the proposed fitness-function, the following points of discussion are shown for the proposed study.

- simulation parameters of GA and TLBO algorithm are given in Table 1
- firing angles for the TLBO algorithm are presented in Figure 4
- the 5th order harmonics versus modulation index graph is shown in Figure 5
- the 7th order harmonics versus modulation index graph is shown in Figure 6
- the 11th order harmonics versus modulation index graph is shown in Figure 7
- the optimised THD profile versus modulation index graph is shown in Figure 8
- THD profile comparison between the performance of TLBO and GA algorithms is shown in Figure 9
- line voltage waveform and THD profile using MATLAB Simulink, and experimental verification of THD is represented in Figures 12, 13, 14 and 15 respectively
- a tabulation of minimum THD obtained, the value of the corresponding modulation index, and related switching angles are presented in Table 2

- a tabulation of THD obtained in various literature is compared with the proposed work is presented in Table 3.

The values of the simulation parameters used in GA and TLBO algorithm are given in Table 1.

Table 1 Simulation parameter for running GA and TLBO on MATLAB

Algorithm simulation parameters		*Values obtained using proposed novel fitness function*
GA	Minimum line voltage THD value	7.56%
	Modulation index for minimum line voltage THD value	0.8
	Number of iterations	100
	Population size	50
	Mutation rate	0.05
	Upper and lower bound considering quarter wave symmetry	0° to 90°
TLBO	Minimum line voltage THD value	5.2%
	Modulation index for minimum line voltage THD value	0.8
	Number of iterations	100
	Number of students (agents)	50
	Upper and lower bound considering quarter wave symmetry	0° to 90°

Firing angles obtained from the combination of TLBO technique and proposed fitness function is seen in Figure 4. It is clear from this data that the fitness function can give a useful range of modulation index from 0.4 to 1.2, which means over modulation is possible with the proposed fitness function. Figures 5, 6, and 7 show the minimised higher-order harmonics. Thus it is clear that harmonic elimination is also possible with THD minimisation. Figure 8 shows the THD profile obtained using the proposed fitness function and TLBO algorithm. It is evident that, although the THD minimisation is applied on phase voltage rather than line voltage, the minimum THD at $M = 0.8$ is 5.2% in line voltage of three-phase seven-level CHB-MLI with proposed fitness function. Figure 9 shows the comparison between the genetic algorithm (GA) and TLBO algorithm performance on the optimisation of the proposed fitness function. It is also clear that the proposed fitness function optimises in the best manner with the parameter less and robust TLBO algorithm.

Results in this article are obtained from MATLAB Simulink 2019(b) version. For verification of simulated results three-phase seven-level inverter hardware is prepared with nine isolated DC supplies for each H-bridge as shown in Figures 10 and 11. Each DC voltage in simulation model as well hardware is set for giving constant 13 V supply.

The controlling pulses for MOSFETs used in the three-phase circuit are obtained from an Arduino MEGA 2560 controller board. The output of control board is given to IR2110 MOSFET gate driver ICs through opto-coupler 4N35 ICs.

Figure 4 Firing angles based on the TLBO algorithm for proposed fitness function (see online version for colours)

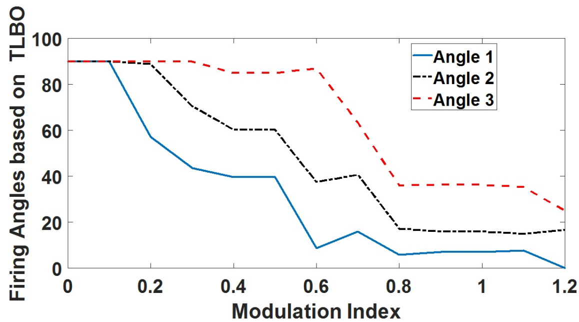


Figure 5 Line voltage 5th harmonic profile based on TLBO algorithms for proposed fitness function

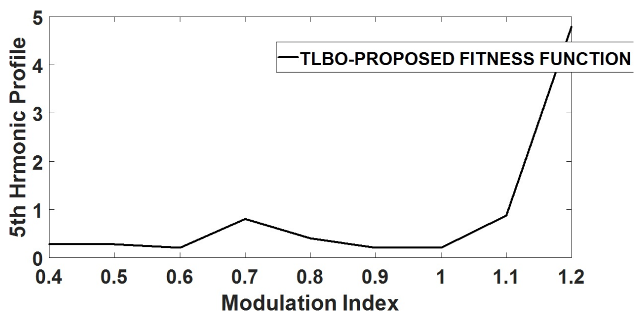
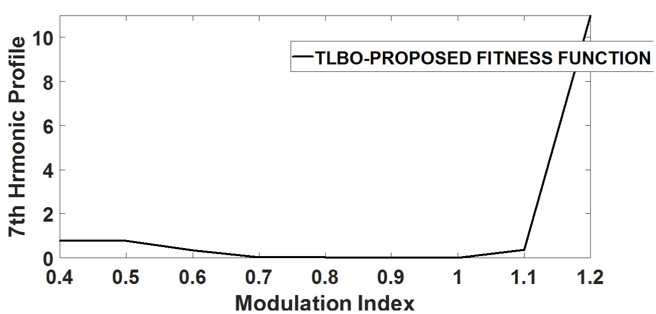


Figure 6 Line voltage 7th harmonic profile based on TLBO algorithms for proposed fitness function



The measurement of line voltage waveform and FFT of the line voltage are measured with SIGLENT SDS1052DL+, two channels DSO. Figure 10 shows the three-phase seven-level hardware details and Figure 11 shows the hardware setup with SIGLENT SDS1052DL+ digital oscilloscope.

Figure 7 Line voltage 11th harmonic profile based on TLBO algorithms for proposed fitness function

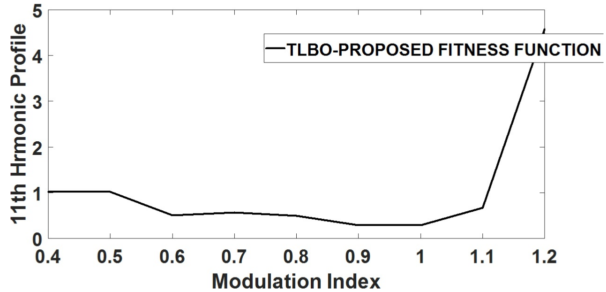


Figure 8 Line voltage, THD profile based on TLBO algorithms using proposed fitness function

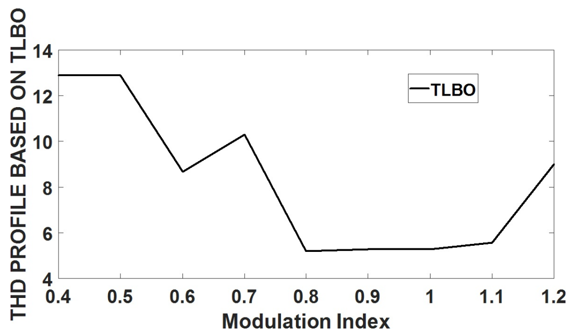
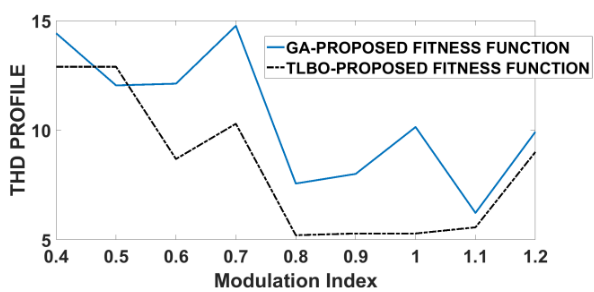


Figure 9 Line voltage, THD profile comparison, based on GA and TLBO algorithms using proposed fitness function (see online version for colours)



Figures 12 and 13 shows the three-phase line voltage of the seven-level CHB-MLI using MATLAB Simulink 2019b software and SIGLENT SDS1052DL+ two-channel DSO result with Probe setting 10X respectively.

Figure 14 gives the THD profile from MATLAB Simulink 2019b for the given seven-level three-phase inverter. It shows the THD value of 5.20 for line voltage waveform. In comparison to the simulation result, the THD profile is obtained from hardware circuit using DSO as shown in Figure 15. It is observed from Figure 15 that in normal view only fundamental component is seen; other harmonic components are very minimal and cannot be observed. THD is calculated for hardware results and tabulated in Table 2.

Figure 10 Three-phase seven-level inverter hardware circuit (see online version for colours)

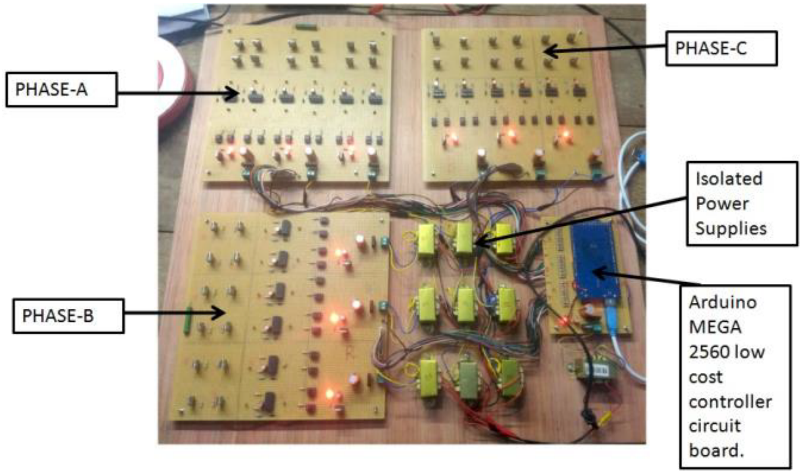


Figure 11 Three-phase seven-level inverter hardware setup with SIGLENT SDS1052DL+ two-channel DSO result (with Probe setting 10×) (see online version for colours)

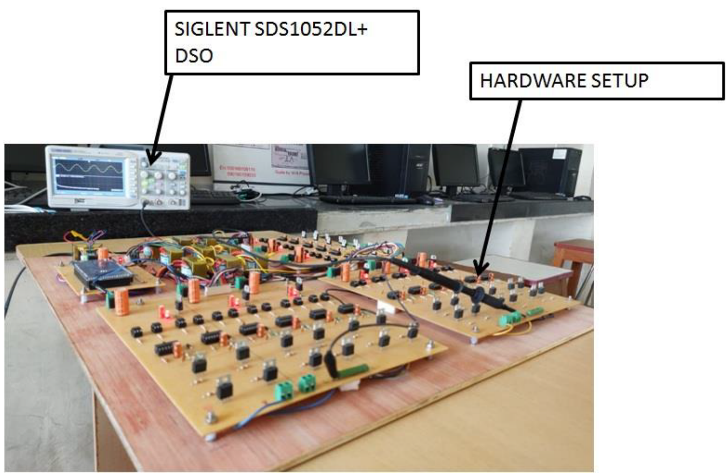


Figure 12 Line voltage waveform for $M = 0.8$ and proposed fitness function for three-phase, seven-level CHB-MLI using TLBO (see online version for colours)

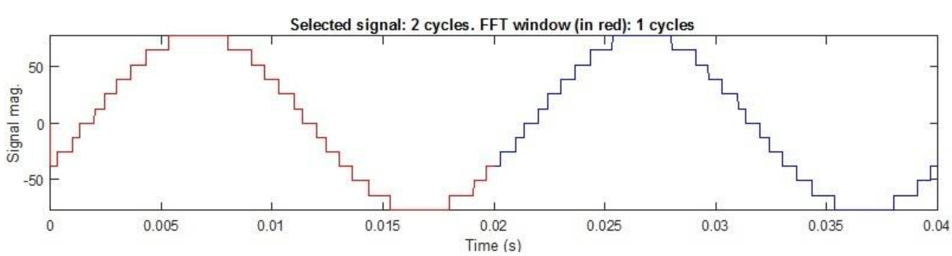


Figure 13 Line voltage waveform for $M = 0.8$ and proposed fitness function for three-phase, seven-level CHB-MLI using TLBO (SIGLENT SDS1052DL+ two-channel DSO result with Probe setting 10×) (see online version for colours)

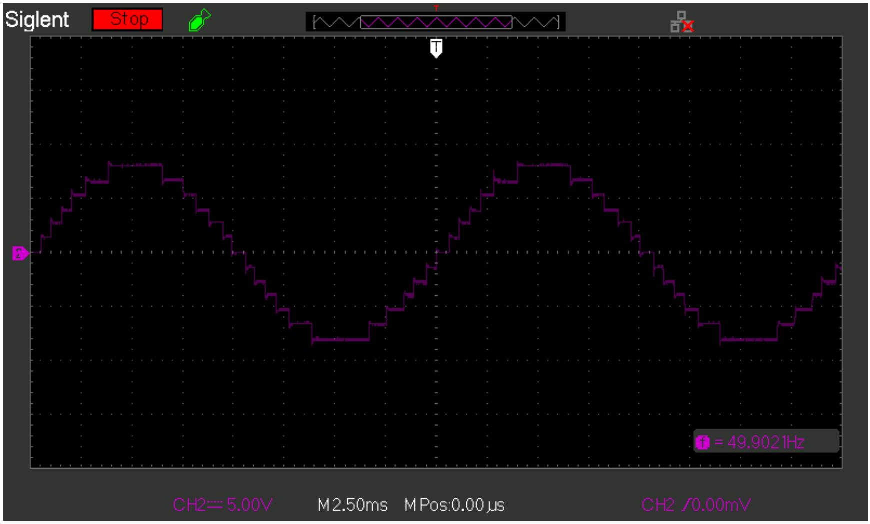
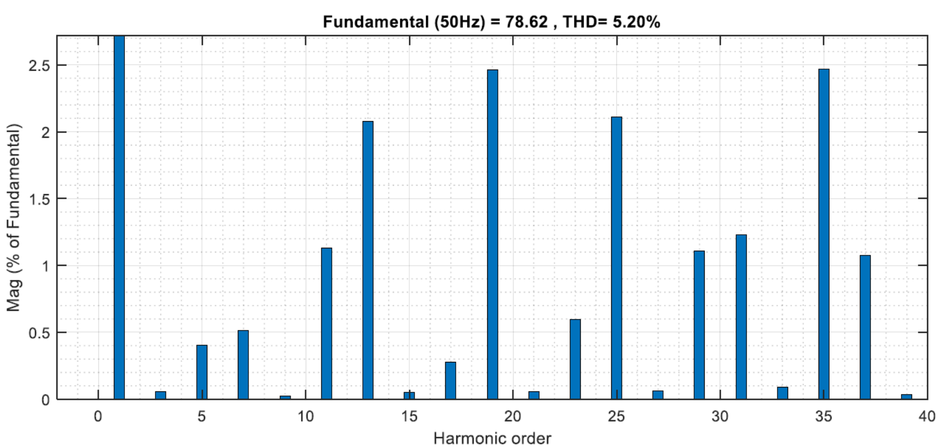


Figure 14 FFT window for line voltage waveform for $M = 0.8$ and proposed fitness function for three-phase, seven-level CHB-MLI using TLBO (see online version for colours)



The values of switching angles related to the minimum value of line voltage and the THD with respect to the modulation index are given in Table 2. It should be noted that the firing levels available in Table 2 are applicable to low, medium and high values of voltage, current and power delivered to the load. Authors have simulated low, medium and high voltage, current and power outputs with same firing angles, and repeatedly same line voltage THD is obtained in all cases. The results are omitted here to optimise size of this article.

Table 2 Line voltage THD's minimum value, firing angles, and modulation index

M	α_1	α_2	α_3	*Line THD value (simulated)*	*Line THD value (calculated from hardware output)*
0.8	5.718	17.189	35.916	5.2%	5.22%

Figures 4 to 9 represent the superiority of the proposed fitness function and TLBO algorithm over other methods discussed in various literatures. More insight into the comparison of work done in this research paper is compared with results obtained in other literature in Table 3.

Table 3 Comparison of minimum THD values in various surveyed literature

Reference no.	*The method used for THD minimisation*	*Minimum THD available in the study*	*THD measurement at line/phase voltage*
Manohar et al. (2016)	THD minimisation using TLBO and NR method	6.95%	Line voltage THD
Kumar and Thangavelusamy (2019)	A modified nearest level scheme is used for THD minimisation	10.2%	Line voltage THD
Jannati-Oskuee (2017)	THD optimisation directly applied online voltage with alterable DC sources	5.95%	Line voltage THD
Fathi and Bakhshizadeh (2012)	THD optimisation directly applied to line voltage using the genetic algorithm.	6.1%	Line voltage THD
Fathi et al. (2009)	THD optimisation directly applied to phase voltage using the homotopy algorithm.	6.78%	Line voltage THD
Khamooshi and Moghani (2014)	THD optimisation directly applied to phase voltage using the BAT algorithm and alterable DC sources.	12.71%	Phase voltage THD (line voltage THD not specified)
Khamooshi and Namadmalan (2016)	A switch utilisation ration scheme is used for THD minimisation.	6.23%	Line voltage THD
Mardaneh and Golestaneh (2013)	THD optimisation directly applied on phase voltage using TLBO algorithm	8.1%	Line voltage THD
Olamaei and Karimi (2018)	THD optimisation directly applied on phase voltage using TLBO algorithm	10.33%	Line voltage THD
Proposed fitness function with TLBO algorithm in present research paper	A proposed fitness function in the present research article discussed in Section 2 is optimised with TLBO algorithm	5.2%	Line voltage THD

Figure 15 FFT window for line voltage waveform for $M = 0.8$ and proposed fitness function for three-phase, seven-level CHB-MLI using TLBO (SIGLENT SDS1052DL+ two-channel DSO result with Probe setting 10×) (see online version for colours)

5 Conclusions

A three-phase seven-level CHB-MLI is considered in the present study of THD minimisation for EVs considering the combination of CHB-MLI, and three-phase induction motor as a best suitable candidate for the low-cost electrical vehicle for many recent and future researches. For THD minimisation, a fitness function is proposed in this research paper. The proposed fitness function is optimised for phase voltage THD minimisation with the TLBO algorithm. The combination of proposed fitness function and TLBO algorithm produces firing angles for a wide range of modulation index.

In the present study, it is concluded that the lower order harmonics that are 5th, 7th, and 11th order harmonics are significantly removed from the output, as seen in Figures 5, 6, 7, 14 and 15. The minimum value of line voltage THD obtained using the proposed approach is 5.2% at a modulation index value of 0.8, which is below the IEEE standards. The results are also experimentally verified using a three-phase seven-level inverter hardware.

It also concluded that the combination of proposed fitness function and the parameter less TLBO algorithm gives the best solution for low-cost EV and HEV motor performance and THD minimisation for wide range of modulation index. Moreover low frequency switching scheme using selective harmonic elimination would also increase the life of EV and HEV. Micro and major solar power plants can use the results shown in the article to reduce the harmonic injection in the existing power grid. Most of the industrial drives use induction motors till date. The proposed low-cost strategy and results can be implemented in industrial drives to improve the machine life.

Researchers can consider the study for their future research with higher number of levels. Increased number of levels with the proposed study would give almost near sinusoidal line voltage finding its path in numerous industrial applications.

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Appendix

Explanation of the term $3M$ in equations (5) and (14) is given as below.

From equation (4) of this article the per phase output voltage of the seven-level inverter is given by,

$$v(1) = \frac{4V_{DC}}{\pi}\left[\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)\right] \tag{19}$$

Also modulation index is given by,

M = Required fundamental value of voltage output / Maximum possible voltage output

Equation of modulation index is written as shown in equation (15) in this article.

$$M = \frac{V_1}{\left(\frac{12V_{DC}}{\pi}\right)} \tag{20}$$

Multiplying and dividing right side of equation (19) by 3 and rewriting, equations (21) and (22) are obtained respectively.

$$\frac{3}{3}\times\frac{v(1)}{\frac{4V_{DC}}{\pi}}=\left[\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)\right] \tag{21}$$

$$\frac{3}{1}\times\frac{v(1)}{\frac{12V_{DC}}{\pi}}=\left[\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)\right] \tag{22}$$

The term $\frac{v(1)}{\frac{12V_{DC}}{\pi}}$ in equation (22) is modulation index M as given in equation (20).

$$3\times M=\left[\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)\right] \tag{23}$$

Thus in equations (5) and (13) the term $3M$ come in to picture.

$$\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)=3M \tag{24}$$