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Application of Teaching - Learning - Based Optimization in Solving Selective Harmonic Elimination Problem of Multilevel Inverters

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Abstract

Selective harmonic elimination (SHE) is a powerful modulation scheme aims to find the required switching angles in order to eliminate the number of undesired harmonics. SHE is a complicated problem which consists of several nonlinear equations which have multiple local minima. In order to eliminate the higher number of undesired harmonics and as a result reducing the total harmonic distortion (THD) much more efficiently, the degrees of freedom must be increased. This means that the number of switching angles gets more and as a result, the problem gets more intricate. As the number of switching angles increases, using either traditional iterative techniques or resultant theory method gets useless. So, in this paper, SHE is treated as an optimization problem where Teaching–Learning-Based Optimization algorithm (TLBO) is found as an efficient tool to solve it. The provided experimental and simulation results of a 7-level multi-level inverter validate the efficiency and practicability of the implemented scheme.

Keywords: Selective Harmonic Elimination; Teaching–Learning-Based Optimization; Multilevel Inverter.

Nomenclature	
s	*Number of DC voltage sources*
k	*Number of switching at each level*
n	*Harmonic order*
V_{DC}	*Nominal DC voltage*
V_1	*Magnitude of fundamental frequency of voltage waveform.*
θ_i	*Optimum switching angles where i=1, 2,…, 9*
M	*Modulation index*

1. Introduction

Multilevel inverters have been dedicated more attention in the recent years. Stepwise output voltage is the priority of multilevel inverters in comparison with conventional two level inverters. The main advantages of multilevel inverters are better Electromagnetic Capability (EMC), lower switching losses, higher power quality, reduction of dv/dt stresses, lower total harmonic distortion (THD), needlessness of a transformer at distribution voltage and lower rating on power semiconductor switches [1-2]. Based on these advantages, multilevel inverters can be used in the industrial application such as: distributed generation, micro grids, FACTs devices, and High Voltage Direct Current (HVDC) [3-6]. Three more common categories of multilevel inverters are: flying capacitor [7], diode clamped [8] and cascaded multilevel inverters [9]. Related to the inverter circuit topologies the DC sources can be interconnected or isolated. The stepwise output voltage of multilevel inverters is obtained from a number of DC voltage sources connected to the input terminals [10]. If the number of output voltage steps in the multilevel inverter increases, the output voltage THD will be reduced. However, the number of these levels is restricted by such factors as voltage unbalance, circuit layout and voltage clamping issues. Switching strategy affects the performance of multilevel converters. In this regards different control methods have been used in many articles to improve the quality of output waveform and reach the minimum value of THD. Some of the well-known switching strategies are pulse width modulation (PWM), sinusoidal pulse width modulation (SPWM), space vector modulation, minimization of THD and selective harmonic elimination (SHE) [11–13].

SHE is a modulation strategy which its goal is to eliminate the number of low order harmonics. This causes to minimize the output voltage waveform THD and simultaneously the fundamental component reaches to the desired value through proper switching angles [14].

The defined objective function for SHE problem includes a set of non-linear transcendental equations which may involve several local optima. Because of the intricacy of the problem, in most studies on the SHE, it's assumed that only one switching angle per each voltage level is defined and the dc voltage sources are balanced (equal to each other). But in practical applications, depending on the output waveform and operation scheme of the inverter, the dc sources could be unbalanced or several switching per each level are involved [15-16]. Solving the SHE problem is available with the help of several procedures. Resultant theory is based on methodical calculations [17]. In Resultant theory method the provided equations which are defined for SHE are converted into an equivalent set of polynomial equations and then, resultant theory is applied to the obtained equivalent equation which is naturally

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high-order polynomials. The main problem with this method is the complexity of calculation. The complexity increases when the number of switching angles is increased and so, makes the equivalent equation harder to be solved or even not be solved. Another approach for solving SHE is the Newton–Raphson method and it is a Numerical iterative technique [18]. However, the great difficulty of these techniques is the proper initial guess requirement that should be near to the exact solution. It's evident that giving a proper guess is very difficult in most cases but if a proper initial guess is available, Newton–Raphson method works properly. This difficulty is the result of the SHE problems search space which is unknown for any body and no one knows whether a solution exists or not, and if exists, what is the proper initial guess? A recently developed novel method to deal with the SHE problem is based on evolutionary algorithms such as Bee algorithm [19]. However the search spaces intricacy will increase vividly, if the number of switching angles increases and both methods fall into the trap of local optimum points of search space. Surely, the precise limitation for the number of switching angles cannot be determined in evolutionary algorithms. So, increasing the number of switching angles reduces the probability of finding the optimum switching angles, unfortunately. The SHE-PWM is a novel method that provides a large number of the degrees of freedom (DOFs) and makes available to eliminate more harmonic components with no need to change the perceivable hardware of the inverter [20]. In SHE-PWM, each active device can be switched at least twice per cycle, and larger number of harmonic components than in the case of fundamental frequency switching scheme can be eliminated. In this paper, a novel method based on TLBO is developed to deal with the SHE-PWM problem. Simulation and experimental results are obtained for a 7-level cascaded multilevel inverter to validate the efficiency of the proposed method and accuracy of the obtained results. Also, in order to validate the efficiency of the proposed approach, a comparison is provided with the most popular optimization algorithm. The provided comparison shows that, TLBO is more efficient in solving of SHE.

2. Selective Harmonic Elimination

SHE method is applied on the staircase voltage waveform of multilevel inverters [21-23]. With consideration of s-DC voltage sources, 2s+1-level can be produced in the output voltage waveform. Also, if the number of switching in a quarter of cycle is limited to s, it will be possible to eliminate $s-1$ harmonics of output voltage. In order to increase the degrees of freedoms and elimination of more harmonics without any manipulate on inverters hardware, the SHE-PWM technique is suggested. This technique is one of the most efficient methods applied to multilevel inverters, that leads to a qualitatively different waveform with less switching frequency in comparison with other PWM methods. The number of switching at each level is supposed to be equal in this study. If k indicates the number of switching at each level, switching frequency of the SHE-PWM scheme will be k times the fundamental frequency. So, the number of harmonic components that can be eliminated from the output voltage is evaluated by $k \times s-1$. A 7-level inverter including 3-DC voltage sources is defined as a case study to assess the impact of SHE-PWM on its harmonic spectrum. A half cycle of a typical waveform of the reference phase voltage of a 7-level inverter synthesized by several DC sources using SHE-PWM method is illustrated in Fig. 1. For the 7-level inverter and considering three times of switching at each level ($k=3$), there are 9 ($\theta_1-\theta_9$) degrees of freedoms, and so 8 undesired harmonics can be eliminated from the output voltage of Inverter. The $\theta_1-\theta_{ks}$ are the required switching angles to specify the whole cycle of the shown waveform. The Fourier expansion for the voltage waveform which is generated by SHE-PWM method [24], can be expressed as (1). The rising edges of the voltage waveform are shown by the positive signs in (1) and the negative signs show falling edges of the waveform. The SHE PWM method can eliminate the non-triple lower order harmonics up to $3ks-2$ when ks is odd and up to $3ks-1$ order harmonic while ks is even. It's ignorable to eliminate the triple harmonics for three-phase applications since these harmonics automatically are removed from the line voltage. Modulation index (M) is defined as (2):

$$M=\frac{V_1}{sV_{DC}} \qquad (2)$$

For a 7-level inverter, related equations based on (1) consist of 9-nonlinear equations that one equation is for fundamental component and the other ones are related to the undesired harmonics (3).

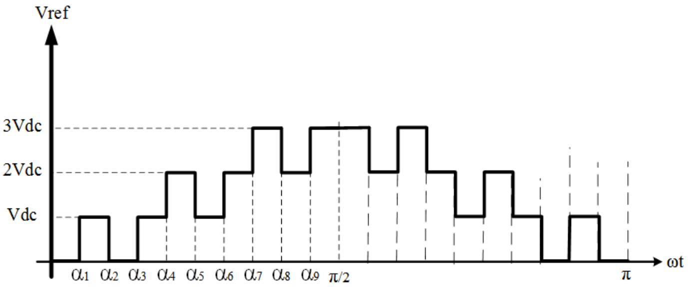


Fig. 1. Half cycle of the reference phase voltage of a 7-level inverter

$$V(wt)=\sum_{n=1,3,5,..}^{\infty}\frac{4V_{DC}}{n\pi}\left(\cos(n\theta_1)\pm\cos(n\theta_2)\pm\cos(n\theta_3)\pm...\pm\cos(n\theta_{ks})\right)=\sum_{n=1}^{\infty}V_n\sin(nwt) \qquad (1)$$

$$\left\{\begin{array}{l}\cos(\theta_1)-\cos(\theta_2)+\cos(\theta_3)+...-\cos(\theta_8)+\cos(\theta_9)=\left(s\pi/4\right)M\\ \cos(5\theta_1)-\cos(5\theta_2)+\cos(5\theta_3)+...-\cos(5\theta_8)+\cos(5\theta_9)=0\\ \cos(7\theta_1)-\cos(7\theta_2)+\cos(7\theta_3)+...-\cos(7\theta_8)+\cos(7\theta_9)=0\\ \vdots\\ \cos(25\theta_1)-\cos(25\theta_2)+\cos(25\theta_3)+...-\cos(25\theta_8)+\cos(25\theta_9)=0.\end{array}\right\} \qquad (3)$$

$$f(\theta_1,\theta_2,...,\theta_{ks})=100\times\left[\left|M-\frac{|V_1|}{sV_{DC}}\right|+\left(\frac{|V_5|+|V_7|+...+|V_{3KS-2or3ks-1}|}{sV_{DC}}\right)\right] \qquad (4)$$

The objective of SHE-PWM method is aimed to choose the set of switching angles ($\theta_1-\theta_9$) such that the identified lower order harmonics are suppressed, and at the same time, the amplitude of fundamental component becomes equal to the desired value. Given the previous descriptions, the objective function [24] is illustrated by the expression (4). The switching angles used in (4) must satisfy the following basic constraint:

$$0\le\theta_1\le\theta_2\le...\le\theta_9\le\frac{\pi}{2} \qquad (5)$$

3.Teaching-Learning-BasedOptimization (TLBO)

The objective function aims to satisfy the desired value of fundamental component and eliminating undesired harmonics. Proper switching angles must be obtained to meet objective function. In this paper TLBO is adopted to solve the defined problem. TLBO is a novel efficient optimization algorithm, which its initial version has been enhanced [25-27]. It is employed in many applications to solve the defined problem due to its high efficiency which means good convergence speed and global minimum achievement. This algorithm is based on the effect of a teacher on learners that simulates the teaching–learning phenomenon of a classroom in order to solve multi-dimensional, linear and nonlinear problems with sensible efficiency. TLBO, like other nature-inspired algorithms, is a population-based method where the population is considered as a group of learners or a class of learners and the different subjects offered to the learners are analogous with the different design variables of the optimization problem. Any algorithm-specific control parameters are not required in the algorithm of TLBO. It needs only common controlling parameters like population size and number of generations (and elite size, if considered), thus, it could be considered as an algorithm-specific parameter-less algorithm. SHW-PWM is an optimization problem and thus TLBO is found to be an appropriate way to be utilized in this field. The flowchart of TLBO is depicted in Fig. 2. Defining the principle of TLBO is out of this papers scope but the complete review is given in several papers for instance in [25-27]. According to SHE, variables are the switching angles of a 7-level inverter and TLBO tries to minimize the equation (4), considering the limitations.

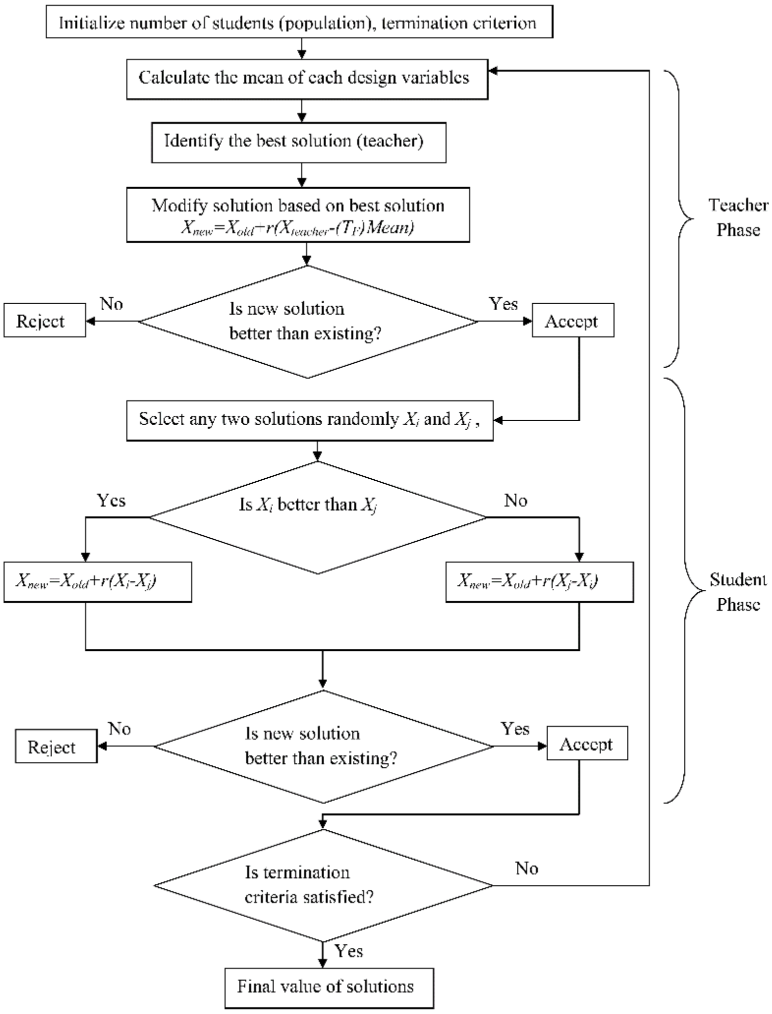


Fig. 2. Flow chart for Teaching–Learning-Based Optimization (TLBO)

4. Simulation Results

SHE method is applied to the 7-level inverter and the results are obtained. The simulation results are carried out on MATLAB/SIMULINK software. TLBO was applied to search the optimal angles of the SHE problem in (4), subject to its limitations. It should be noted that TLBO is run for several times, and then optimal solutions are chosen. The step of M is considered to be 0.005. Fig. 3 represents the cost value of objective function with respect to the modulation index. It is obvious that the TLBO method is effectively able to find the optimum switching angles to suppress the undesired harmonics. The optimum switching angles versus modulation index, are plotted in Fig. 4. SHE aims to satisfy the fundamental component and eliminates the specific undesired harmonics, simultaneously. To validate the ability of TLBO, the fundamental harmonic and both the normalized amplitude of undesired harmonics versus the modulation index are illustrated in Fig. 5. It can be seen from Fig. 5(a) that the fundamental component is always maintained close to the desired value. The simulated values for phase voltage THD and line voltage THD versus modulation index are plotted in Fig. 6, respectively. Based on cost value of objective function, simulation results are presented for M= 1.09. The final optimal switching angles for a 7-level multilevel inverter obtained for M= 1.09 are listed in table 1. In order to validate the efficiency of TLBO generating the desired fundamental component and simultaneously achieve the lower minimum THD, a comparison is provided with genetic algorithm as a popular optimization algorithm commonly used. In this regards, GA algorithm is run for several times and the minimum THD for phase voltage is obtained as 13.41%. In order to provide simulation results, the nominal DC voltage of DC sources is considered to be 10 V. The output phase voltage and line voltage waveforms for M=1.09 and their related FFT analysis are shown in Fig. 7(a)–(d), respectively. From the fast Fourier transform (FFT) analysis of the phase output voltages, it can be seen that the magnitudes of lower order harmonics are negligible.

As the triple harmonics will not be presented in the line voltage, they are not shown in the FFT analysis of line voltage. Figs. 7, validates the ability of obtained switching angles in generation of phase voltage with minimum possible THD.

Table1: Optimal results obtained for line to line THD in cascaded 7-level inverter

THD Line%	THD phase%	M	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9
9.45	13.3	1.09	0.381	0.74	7.99	20.7	22.69	25.39	45.33	49.85	52.87

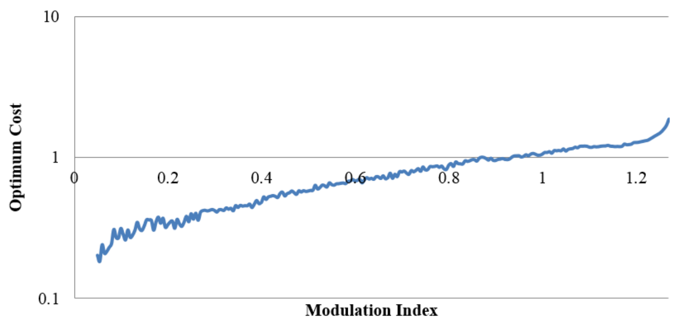


Fig. 3 The optimum value of cost function versus Modulation index

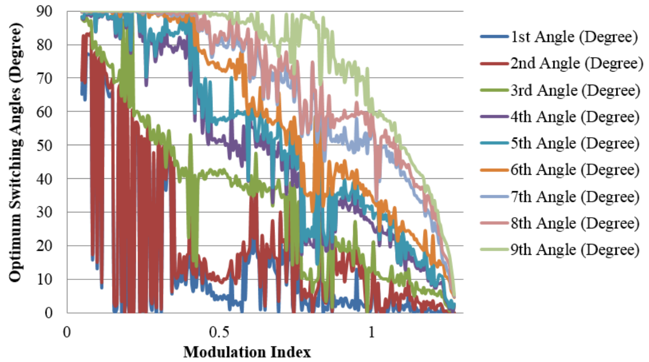
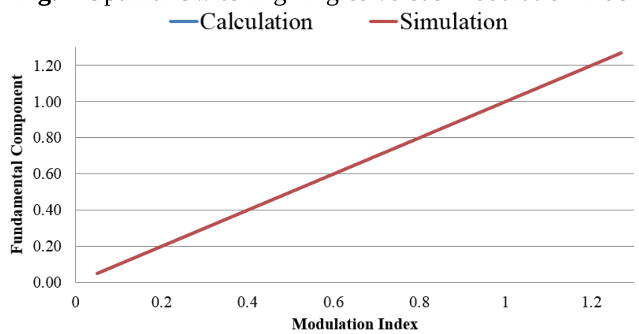
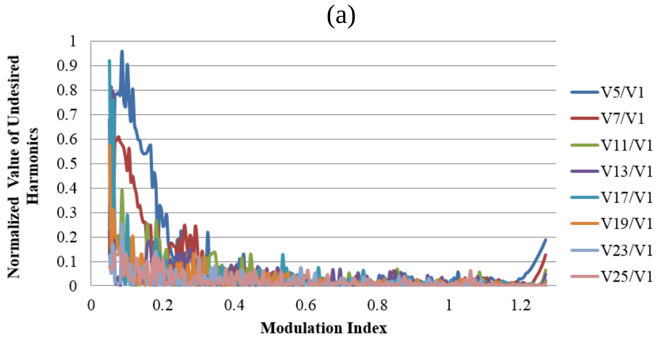


Fig. 4 Optimal Switching Angles versus Modulation Index

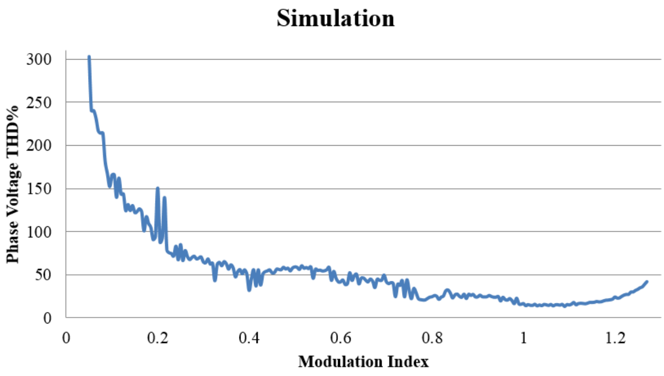


(a)



(b)

Fig. 5; a) Amplitude of fundamental harmonic versus Modulation Index and b) Normalized amplitude of undesired harmonics (V_h / V_1) versus Modulation index



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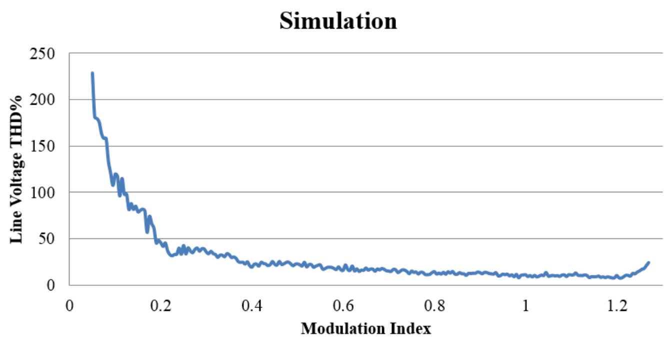
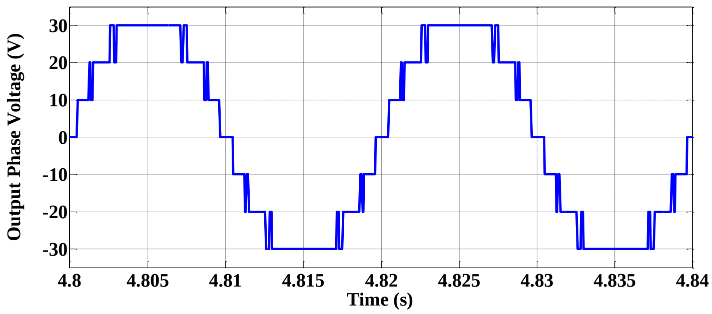
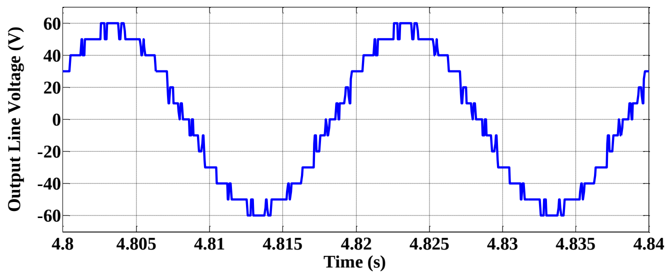


(b)

Fig. 6; a) Phase voltage THD; b) Line voltage THD



(a)



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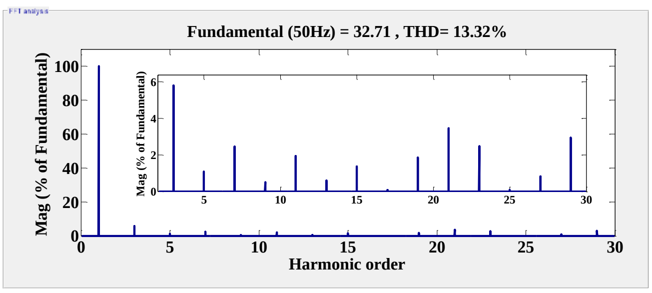
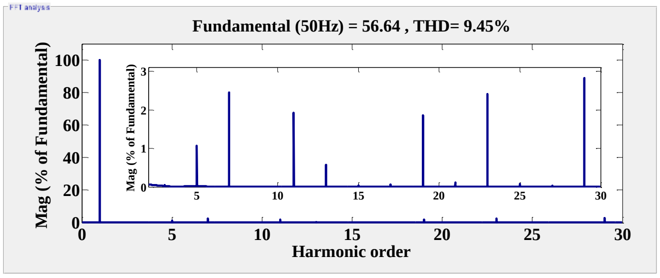


(c)



(d)

Fig. 7. Simulation results of a 7-level multilevel inverter for M = 1.09; a) Output phase voltage; b) Output line voltage; c) FFT analysis for phase voltage and d) FFT analysis for line voltage

5. Experimental Results

In order to validate the effectiveness of the presented method, an experimental prototype of a two phase seven-level inverter has been implemented in this paper. Fig. 8 shows the photograph of implemented prototype. The MOSFETs used for the prototype are IRF 840 with internal anti-parallel diodes and voltage and current ratings equal to 500V and 8 A, respectively. The TLP 250 is used as gate derives.

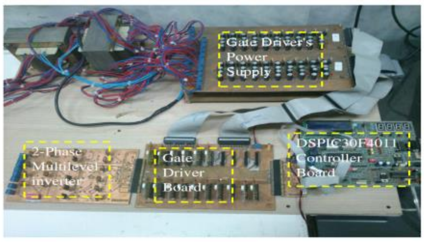
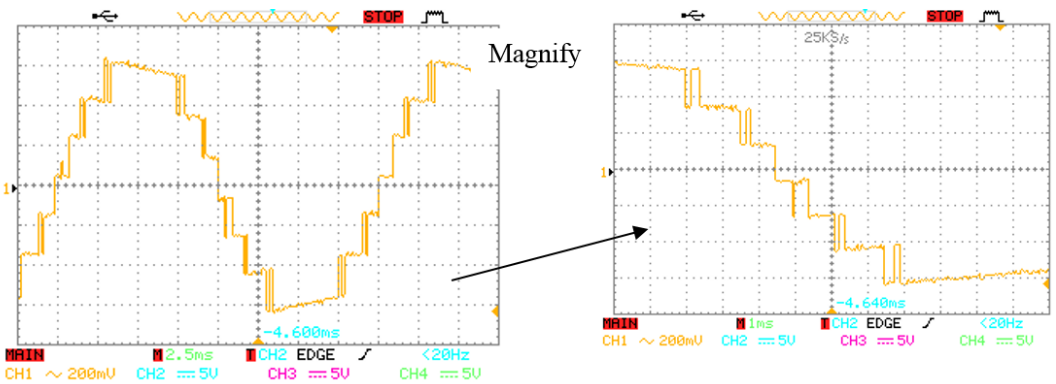
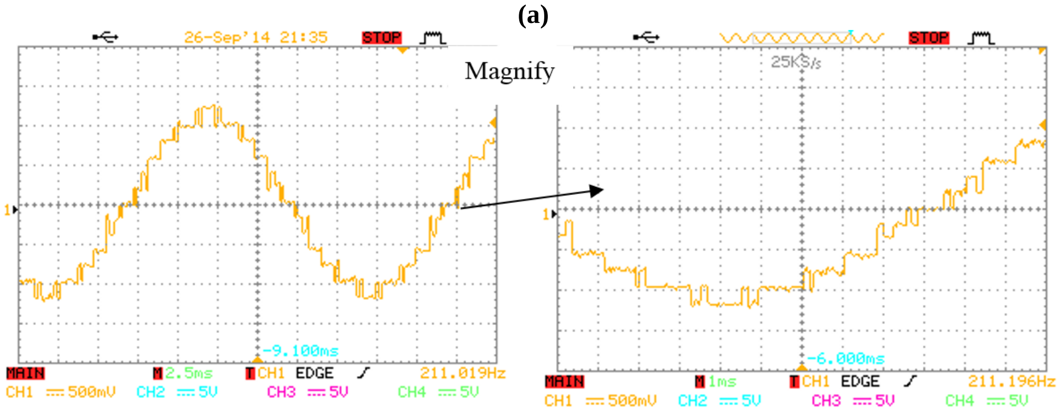


Fig. 8 Implemented prototype setup

In the implemented prototype, the switching angles that listed in tables 1 are applied. Fig. 9 illustrates the experimental results of implemented circuit. It shows the output phase and line voltages of implemented 7-level multilevel inverter for M=1.09. It can be seen from Fig. 9 that voltage waveforms are more similar to simulation results which confirm the implemented method's practiceability. The comparison between Fig. 9 and Fig. 7 shows that simulation and experimental results which validate the accuracy of obtained results from computational equations match thoroughly. Also, partial difference between simulation and experimental results are due to voltage drops on switches.



(a)



(b)

Fig. 9 Experimental results of 7-level inverter for; a) output phase and b) Line voltages for M=1.09

6. Conclusion

In this paper, TLBO algorithm has been proposed to determine the optimum switching angles of a 7-level inverter. This algorithm has been successfully applied to the SHE-PWM problem with higher number of switching angles, where other traditional methods cannot solve it. Simulation and experimental results are provided to approve the accuracy of proposed method. Outcomes show that the defined undesired harmonics have been successfully diminished at the output voltage waveform.

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