U.P.B. Sci. Bull., Series C, Vol. 79, Iss. 1, 2017 ISSN 2286-3540

SOLVING LINE VOLTAGE THD MINIMIZATION PROBLEM IN MULTILEVEL INVERTER'S WITH CONSTANT DC VOLTAGE SOURCES USING TEACHING-LEARNING-BASED OPTIMIZATION

Javad OLAMAEI[1], Masoumeh KARIMI[2], Tohid FARHOUDI[3]

Total Harmonic Distortion (THD) is a very important factor to examine harmonic contents of waveforms. In this paper, THD of the line output voltage of multilevel inverters can be drastically minimized with an appropriate switching scheme. Phase voltage THD minimization has simple computation but the same method cannot be useful for line voltage THD minimization. So, line voltage THD minimization is one of the most important requirements from the load point of view. In order to obtain best switching angles to descend output line voltage THD, Teaching-Learning-Based Optimization (TLBO) algorithm is applied. The obtained results from TLBO which shows the efficiency of this method, are compared with the recently published article using GA. Simulation and experimental results are clear represented for a test case seven-level inverter to validate the studies.

Keywords: THD Minimization, Teaching-Learning-Based Optimization, Line-To-Line voltage

1. Introduction

Recently, a tendency to multilevel inverters as new kind of converter is increased from power electronic engineering point of view. Switches and capacitor voltage sources provide the arrangement of the multilevel inverters structure. Multilevel inverters have capability to provide staircase output voltage with a low harmonic distortion while the switching strategy is correctly controlled [1]. There are many DC voltage sources to generate the staircase output voltage waveform of multilevel inverters [2]. According to multilevel inverter topologies, the inverter output voltage waveform can reach quite close to sinusoidal waveform if the number of steps are increased while a fundamental frequency scheme is applied [3]. For most of applications, multilevel inverters are emerging as a viable alternative because of their higher power quality, more electromagnetic capability, lower switching losses, voltage capability, higher efficiency, lower

[1] Department of Electrical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran, e-mail: j_olamaei@azad.ac.ir
[2] Electrical Engineering Department of Azarbaijan Shahid Madani University, Tabriz, Iran
[3] Electrical Engineering Department of Azarbaijan Shahid Madani University, Tabriz, Iran

dv/dt, and lower THD [4-6]. Multilevel Inverters are one of the most popular and useful inverters which are applied to applications such as: Distributed Generation (DG) [7], micro grids [8-9] and Flexible Alternating Current Transmission System (FACTS) equipment [10-11]. Three basic classifications of multilevel inverters are: Cascaded H-Bridge Multi-level Inverters (CHML) [12], Diode Clamped Multilevel inverters [13] and flying capacitor multilevel inverters [14]. If efficient modulation strategies apply, the inverter's efficiency and quality of output voltage waveform will be improved. So, because of many different switching strategies, multilevel inverters are being used in many applications [15-16]. There is many research in the field of modular multi-level inverters to improve the quality of output waveform. Several common modulation techniques are Sinusoidal Pulse Width Modulation (SPWM) [17], Selective Harmonic Elimination (SHE) [18], Minimization of the Total Harmonic Distortion [19-21] and space vector modulation [22]. Main comparison between THD and SHE strategies shows the removing of some low-order harmonic components in SHE strategy while the fundamental frequency is remained, but in minimization of THD strategy, all of the harmonic components are minimized while the fundamental component is prepared. The possible minimum THD value is achieved when the desired amplitude of the fundamental component is obtained. THD minimization strategy is more effective in decreasing the THD between the above-mentioned strategies. For THD minimization and SHE methods, the output voltage waveform of the inverter is supposed as a stepwise waveform with fundamental frequency. In order to decrease THD and improved the output voltage quality, various carrier pulse width modulation strategies are introduced [23]. Because of unique and simple form of phase voltage waveform of multilevel inverters, it has simpler comparing than its line voltage waveform. So, usually THD minimization methods are implemented to phase voltage. In other words, minimizing phase voltage of the inverter cannot lead to a minimum value for line voltage minimization. Line voltage is vitally important requirement from the load point of view. In [20, 24] line to line voltage THD minimization has been studied. Since, the THD is exclusively relevant data to the voltage, a lot of studies are concentrated on line voltage THD. In the present paper, recently developed metaheuristics called teaching-learning-based optimization (TLBO) algorithm is used to deal with the problem of minimizing THD. The efficiency of the offered method is proved by simulation and experimental results which are prepared for a test case seven level inverter. TLBO shows the best and more efficient results than other approaches compared with the results given in the recently published paper using GA. The remaining of the paper is organized as follows: Section 2 discusses the output voltage waveform of multi-level inverters. Section 3 deals with THD minimization more detailed. In section 4, TLBO Algorithm is described. Implementation of TLBO for optimization is explained in section 5. In Sections 6 and 7 simulation and experimental results are presented, respectively. And at last section 8 is specified to the conclusion.

2. Multi level inverter's output voltage

The output staircase waveform of the reference phase voltage of seven level inverter provided by three DC links is illustrated in Fig. 1.

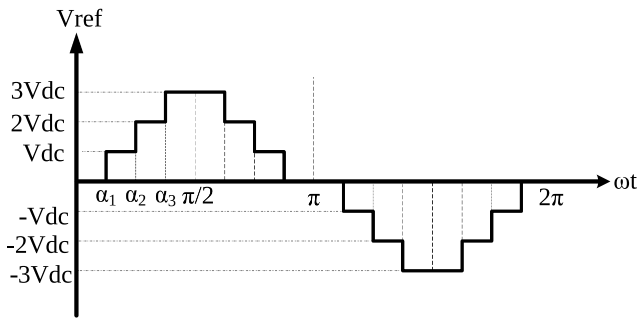


Fig. 1 Typical reference phase voltage of a seven level inverter

It can be shown that the three switching angles, (α1, α2, α3), are required to determine the full-cycle switching pattern. Concerning Fig.1, the voltage waveforms, V_a, can be defined in terms of step function $u(\omega t)$:

$$V_a = \sum_{i=1}^{3} V_{dc}(\mathrm{u}(\omega \mathrm{t} - a_i)) - \sum_{i=1}^{3} V_{dc}(\mathrm{u}(\omega \mathrm{t} - \pi - a_{4-i})) - \ldots \quad (1)$$
$$\sum_{i=1}^{3} V_{dc}(\mathrm{u}(\omega \mathrm{t} - \pi - a_i)) + \sum_{i=1}^{3} V_{dc}(\mathrm{u}(\omega \mathrm{t} - 2\pi - a_{4-i}));$$

Fourier analysis is applied to specify instantaneous values of reference phase voltage. Thus, Fourier analysis is used to calculate V_a and the following term is carried out. The presented periodic waveform of V_a is an odd function and it has odd order harmonics only ($n = 2k \pm 1$).

$$V_a = \sum_{n=1}^{\infty} \frac{4}{n\pi} V_{dc} \sin\left(\frac{n\pi}{2}\right)\left(\cos(na_1) + \cos(na_2) + \cos(na_3)\right)\sin(n\omega t) \quad (2)$$

In spite of the phase voltage, there is no straight procedure for line voltage of multilevel inverters to access the RMS value of the waveform because its form is not unique when switching angles vary. So, in practice this is not desirable to acquire a unique formula for RMS value of line voltage THD for all switching angles. Measurement of instantaneous values is only method to specify RMS value of line voltage which is essential for THD calculation. The waveform of all three phase voltages of multilevel inverter is similar with a phase shift of one third cycle (2pi/3), so the staircase waveform of line voltage can be obtained by subtracting any phase voltage from another one:

$$V_{ab}\left(\omega t\right) = V_a\left(\omega t\right) - V_b\left(\omega t\right) \quad (3)$$

$$V_{ab}(\omega\,\mathrm{t}) = V_a(\omega\,\mathrm{t}) - V_a(\omega\,\mathrm{t} - \frac{2\pi}{3}) \quad (4)$$

Now, a special waveform for line voltage is specified for each value of switching angles. Therefore, the line voltage RMS value can be easily determined by integrating the waveforms rectangular part. The amplitude of fundamental component of phase voltages is equal and there is a 2pi/3 difference in their phases. This leads to the RMS value of the line voltage fundamental component to be $\sqrt{3}$ times that of the fundamental component of the phase voltage. The normalized amplitude of Line voltage fundamental component is given as follows:

$$V_{l1} = \frac{4\sqrt{3}}{3\pi}(\cos\left(a_1\right) + \cos(a_2) + \cos(a_3)) \quad (5)$$

THD can be determined as the ratio of the aggregate of the powers of all the harmonic components to the power of the fundamental frequency. In other words, it is described as the ratio of the RMS amplitude of the higher order harmonic frequencies to the RMS amplitude of the fundamental frequency.

Finally, the line THD is computed using the following equation:

$$THD_{line} = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{V_1^2}} = \sqrt{(\frac{(V_l^2)_{rms}}{(V_{l_1})_{rms}})^2 - 1} \quad (6)$$

3. THD minimization

The main aim of the objective function is minimization of THD value that is one of the most important requirements for multilevel inverters while the amplitude of fundamental component reaches to the desired value. Objective function is minimized to obtain the minimum THD while proper DC source values and switching angles must be obtained. So, in this study TLBO algorithm is applied to solve the aforementioned problem. Because of high efficiency of

TLBO algorithm, which is a new evolutionary optimization strategy, it is employed in several applications to solve the specific problem, good convergence and global minimum achievement. According to the above descriptions, the objective function can be defined as follows:

$$\textbf{Objective}: \ |V_{l1}^{*} - V_{l1}| + THD_{line} \tag{7}$$

where, modulation index is V_{l1}^{*} and varies between 0 to $\frac{4\sqrt{3}}{\pi}$. In simple words, the efforts are to generate the output line voltage which its fundamental component be equal to the modulation index. V_{l1} and THD_{line} are substituted from the related equations obtained in the previous section. The first section of the declared objective function $\left|V_{l1}^{*} - V_{l1}\right|$ is the absolute value of error in adjusting the fundamental harmonic. Based on stated before achievement switching angles which are the solutions of objective function, can satisfy the following basic constraint:

$$0 \le a_1 \le a_2 \le a_3 \le \frac{\pi}{2} \tag{8}$$

Since phase voltage is formulated in noncomplex, the THD minimization can extensively employed to phase voltage more than the line voltage. Nevertheless, this study with constant and alterable DC sources, THD minimization is used to line voltage of a multilevel inverter.

4. Teaching-Learning-Based Optimization (TLBO)

The objective function aims satisfying the desired value of fundamental component (~Modulation index) with possible minimum THD. 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, means good convergence 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 need 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. THD minimization is an optimization problem and thus TLBO is found to be an appropriate way to be utilized in this field. The defined objective function in the TLBO is optimized through the concept of imperialistic competition. 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 THD minimization, variables are the switching angles of a 7-level inverter and TLBO tries to minimize the equation (7), considering the limitations.

5. Simulation Results

THD Minimization method is implemented to the seven-level inverter and the results are obtained. A seven-level inverter is simulated using MATLAB/SIMULINK software to check the accuracy of obtained results for optimum switching angles. First, the TLBO is employed to search the optimal parameters of the TLBO problem in (7), subject to its limitations. It must be noted that TLBO is run for many times until optimal parameters is achieved. The steps of modulation index is considered 0.005. The aim is to satisfy the modulation index following by possible minimum THD_{line}. The cost value of fitness function with the modulation index consideration is illustrated in Fig. 3. TLBO is potentially an effective approach to find the optimum switching angles to suppress the undesired harmonics.

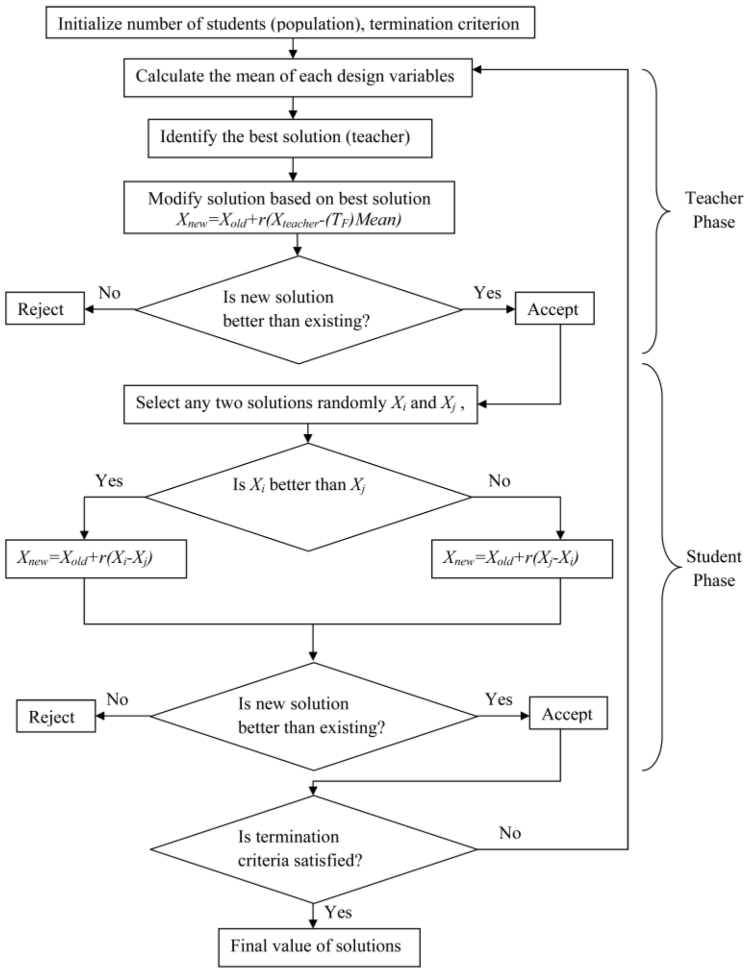


Fig.2. Flow chart for Teaching–Learning-Based Optimization (TLBO).

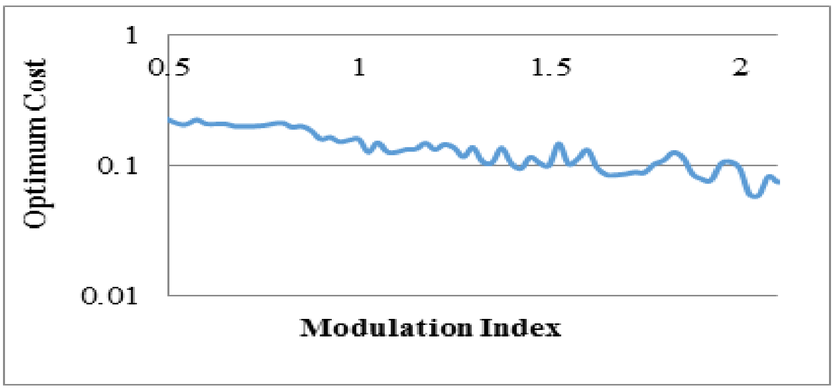


Fig.3. The optimum value of cost function versus Modulation index

Optimal switching angles are achieved when TLBO is used to minimize the Eq. (7). The relation between modulation index and optimal switching angles is demonstrated in Fig. 4.

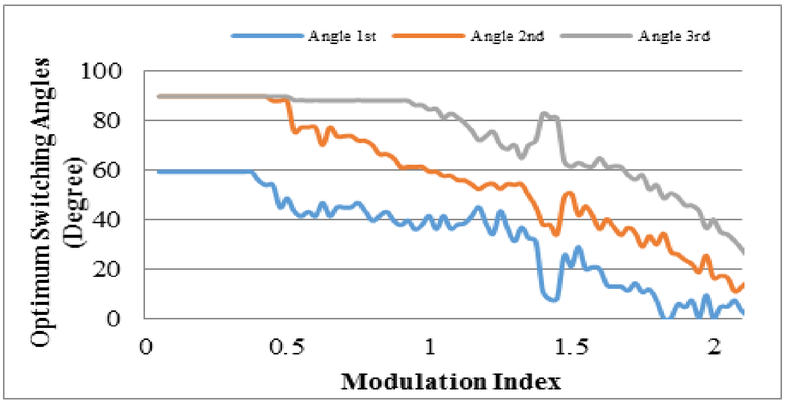


Fig. 4 The obtained switching angles per modulation index

This paper focuses on THD minimization aims to satisfy the fundamental component and minimize the existing harmonics, concurrently. Fig. 4 validates capability of TLBO through the fundamental harmonic versus the modulation index. It can be seen from Fig. 5 that the fundamental component is mostly maintained close to the modulation index.

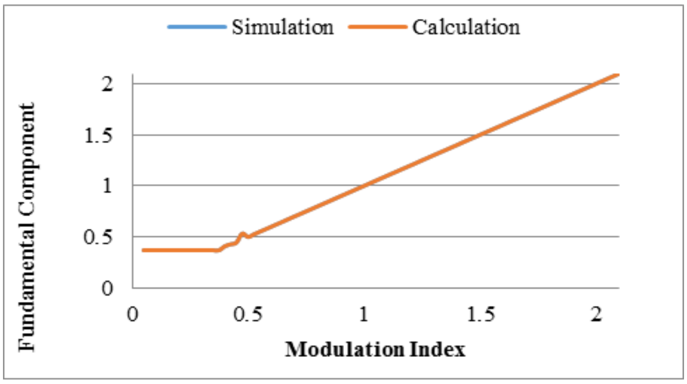
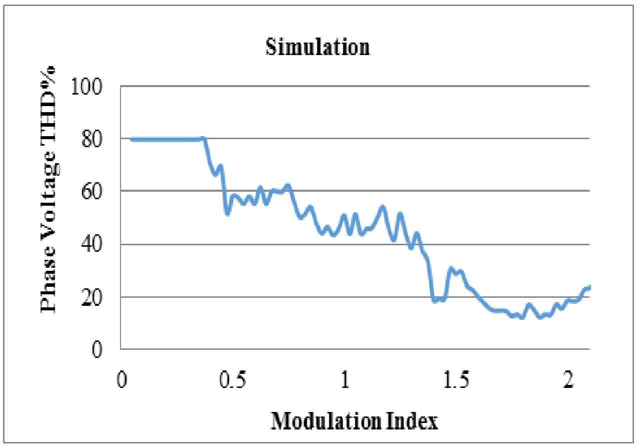
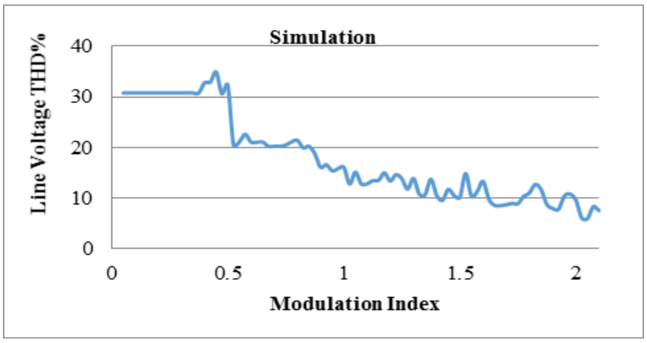


Fig. 5. The fundamental component versus Modulation index

As explained before, the line voltage is the most important parameter because of its harmonic spectrum from the load point of view. Fig. 6 clearly displays the THD values of line voltage and phase voltage. The variance concludes that there is no particular respect between phase voltage THD and line voltage THD and there is no necessity to phase voltage lead to lower THD value while minimum value of the line voltage THD is obtained. Tripled harmonics are absent in line voltage. So, if the THD minimization method is employed to line voltage, optimal state and performance can be specified for the line voltage. In other words, when the accurate value of THD is obtained, accurate optimal angles are extracted.



(a)



(b)

Fig. 6 THD values versus modulation index

In order to achieve optimum condition for the line voltage, the harmonic components appearing at the line voltage are considered during the line voltage THD minimization. In order to show the efficiency of applied algorithm, the value of switching angles on the basis of obtained minimum value of line voltage THD are given in Table I.

Table I

A list of switching angles for Phase THD and Line THD

$V^*_{L_1}$	α_1	α_2	α_3	Phase THD%	Line-To-Line THD%
2.05	4.70	16.40	34.00	18.89	5.98

From the above table, it can be inferred that the least line voltage THD value is achieved by applying TLBO, which is lower than the THD values given in [24] using GA to solve THD minimization problem. So, it validates the sufficiency of TLBO. As a case study the related phase and line voltages for the V^*_{l1} value, given in Table I, and also harmonic content of them are presented in Fig. 7.

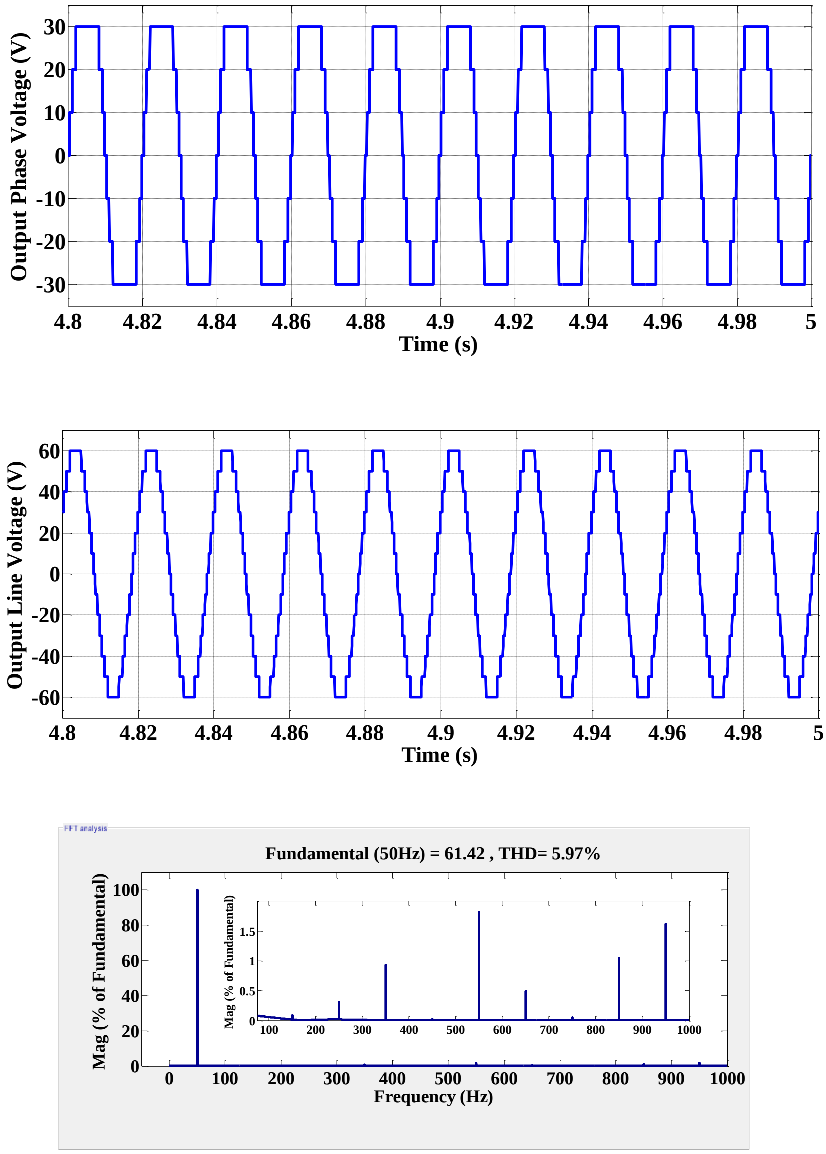


Fig. 7 Phase voltage, Line voltage and the harmonic spectra of Line voltage

The correct generation form of the phase and line voltage which are shown in Fig. 7, validates the accuracy and suitability of the proposed scheme.

6. Experimental Results

An experimental prototype of a two phase seven-level inverter has been tested and applied to validate the effectiveness of presented method in this paper. Fig. 8 shows the photograph of the one phase of two phase implemented inverter.

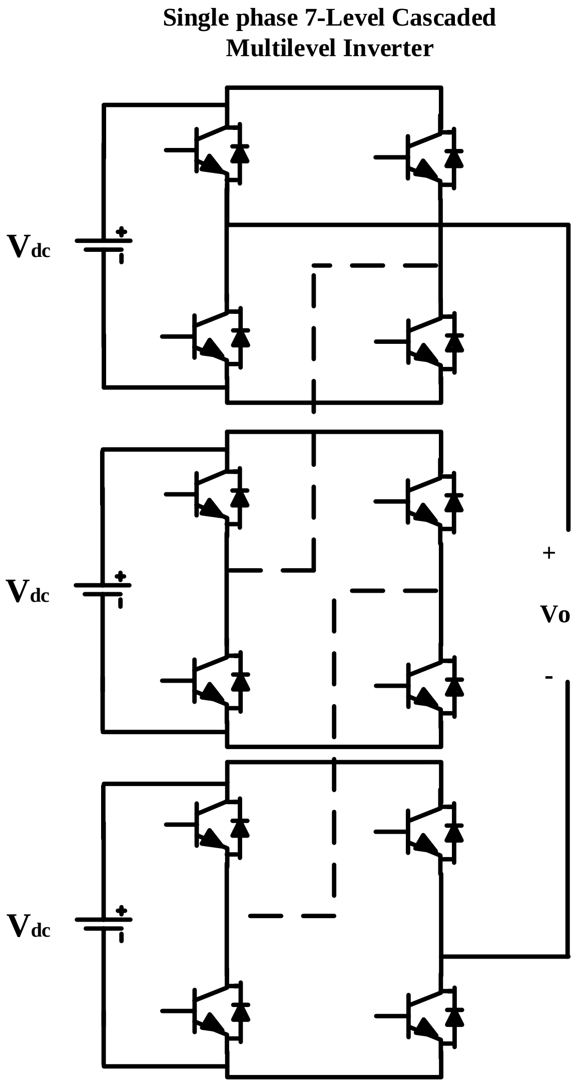


Fig. 8 single phase of implemented two phase 7-level inverter

The MOSFET's 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. The switching angles that listed in Table I, are used in the implemented prototype. Selected experimental results have been provided. Furthermore, matching the results prominently with simulation results makes the efficiency of the proposed approach in THD minimization obvious. Figs. 8(a) and 8(b) show the output phase and line voltages of implemented seven-level multilevel inverter for $V^*_{L_1} = 2.05$. According to these figures, it is clear that the experimental results have a near conformity to the theoretical and simulation results. The waveforms displayed in Fig. 8 as experimental results affirm the simulation results that validate the feasibility of obtained results and capability of the study. Partial difference between simulation and experimental results are due to voltage drops on switches. Because TLBO gave the least value for the line voltage THD minimization in comparison with [24], this paper claims that TLBO is the best choice to solve the phase and line THD minimization problem.

7. Conclusion

Because of simple and rapid formulation, commonly THD minimization methods are implemented to phase voltage. Line to line voltage is significant concern from the load point of view and it is the vital issue in power system engineering. Hence reducing the line voltage THD is a very important problem in three phase applications. In this work, a modern plan of action is presented to minimize THD of line voltage in multilevel inverters. TLBO has a very important role to solve the aforementioned problem to achieve a desirable THD value. Eventually, selected simulation and experimental results have been provided. Then, the accuracy of obtained simulation and practical results are presented and the prepared comparison with previous research demonstrated the efficiency of the proposed approach in THD minimization.

R E F E R E N C E S

[1] *MRJ Oskuee, M Karimi, SN Ravadanegh, GB Gharehpetian*, "An Innovative Scheme of Symmetric Multilevel Voltage Source Inverter With Lower Number of Circuit Devices" Industrial Electronics, IEEE Transactions on 62 (11), 6965 - 6973

[2] *Mohamad Reza Banaei, Mohammad Reza Jannati Oskuee, Farhad Mohajel Kazemi*, Series H-bridge with stacked multicell inverter to quadruplicate voltage levels, IET Power Electron., 2013, Vol. 6, Iss. 5, pp. 878–884

[3] *Mohamad Reza Banaei, Farhad Mohajel Kazemi, Mohammad Reza Jannati Oskuee*, New mixture of hybrid stacked multicell with half-cascaded converter to increase voltage levels, IET Power Electron., pp. 1–9

[4] *Dargahi, V., Sadigh, A.K., Abarzadeh, M., AlizadehPahlavani, M.R., Shoulaie, A.*, 'Flying capacitors reduction in an improved double flying capacitor multicell converter controlled by a modified modulation method', IEEE Trans. Power Electron., 2012, 27, (9), pp. 3875–3887

[5] *MRJ Oskuee, M Karimi, SN Ravadanegh, GB Gharehpetian*," A Developed Single-Phase Cascaded Multilevel Inverter with Reduced Number of Circuit Devices", International Journal of Electronics

[6] *Ebrahimi, J., Babaei, E., Gharehpetian, G.B.*, 'A new topology of cascaded multilevel

converters with reduced number of components for high-voltage applications', IEEE Trans. Power Electron., 2011, 26, (11), pp. 3109–3118

[7] *Ramon Blasco-Gimenez, Salvador A˜n´o-Villalba, JohelRodr´ıguez-D'Derl´ee, Francisco Morant, and Soledad Bernal-Perez*, Distributed Voltage and Frequency Control of Offshore Wind Farms Connected with a Diode-Based HVdc Link, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 25, NO. 12, DECEMBER 2010

[8] *Mohamed A. Eltawil and Zhengming Zhao*, Grid-connected photovoltaic power systems: Technical and potential problems—A review, Renewable and Sustainable Energy Reviews 14 (2010) 112–129

[9] *Alvaro Llaria, Octavian Curea, Jaime Jiménez and HaritzaCamblong*, Survey on microgrids: Unplanned islanding and related inverter control Techniques, Renewable Energy 36 (2011) 2052-2061

[10] *Kyohei Kurohane, Akie Uehara, Tomonobu Senjyu, Atsushi Yona, Naomitsu Urasaki, Toshihisa Funabashi and Chul-Hwan Kim*, Control strategy for a distributed DC power system with renewable energy, Renewable Energy 36 (2011) 42-49

[11] *Pedro Roncero-Sánchez, Enrique Acha, Jose Enrique Ortega-Calderon, Vicente Feliu and Aurelio García-Cerrada*, A Versatile Control Scheme for a Dynamic Voltage Restorer for Power-Quality Improvement, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 24, NO. 1, JANUARY 2009

[12] *F. Peng and J. S. Lai*, "Multilevel cascade voltage source inverter with separate dc sources," U.S. Patent 5 642 275, Jun. 24, 1997.

[13] *Said Barkati, Lotfi Baghli, El MadjidBerkouk, Mohamed-SeghirBoucherit*, Harmonic elimination in diode-clamped multilevel inverter using evolutionary algorithms, Electric Power Systems Research, Volume 78, Issue 10, October 2008, Pages 1736-1746

[14] *Anshuman Shukla, Arindam Ghosh, and Avinash Joshi*, Flying-Capacitor-Based Chopper Circuit for DC Capacitor Voltage Balancing in Diode-Clamped Multilevel Inverter, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 57, NO. 7, JULY 2010

[15] *Tolbert L.M., Habetler T.G.*, 'Novel multilevel inverter carrier based PWM methods', IEEE Trans. Ind. Appl., vol. 35, no. 5, pp. 1098–1107, 1999

[16] *L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo, and M. M. Prats*, "The age of multilevel converters arrives," IEEE Ind. Electron. Mag., vol. 2, no. 2, pp. 28–39, Jun. 2008.

[17] *Mohamed S.A. Dahidah and Vassilios G. Agelidis*, Single-carrier sinusoidal PWM-equivalent selective harmonic elimination for a five-level voltage source converter, Electric Power Systems Research, Volume 78, Issue 11, November 2008, Pages 1826-1836

[18] *A.K. Al-Othman, Nabil A. Ahmed, M.E. Al Sharidah and Hanan A. Al Mekhaizim*, A hybrid real coded genetic algorithm – Pattern search approach for selective harmonic elimination of PWM AC/AC voltage controller, International Journal of Electrical Power & Energy Systems, Volume 44, Issue 1, January 2013, Pages 123-133

[19] *Naeem Farokhnia, HadiVadizadeh, Seyyed Hamid Fathi and Fariba Anvariasl*, Calculating the Formula of Line-Voltage THD in Multilevel Inverter With Unequal DC Sources, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 58, NO. 8, AUGUST 2011.

[20] *Nima Yousefpoor, Seyyed Hamid Fathi, Naeem Farokhnia, and Hossein Askarian Abyaneh*, THD Minimization Applied Directly on the Line-to-Line Voltage of Multilevel Inverters, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 59, NO. 1, JANUARY 2012.

[21] *P. Palanivel S.S. Dash*, Analysis of THD and output voltage performance for cascaded multilevel inverter using carrier pulse width modulation techniques, IET Power Electron., 2011, Vol. 4, Iss. 8, pp. 951–958.

[22] *Lütfü Saribulut, Ahmet Teke and Mehmet Tümay*, Vector-based reference location estimating

for space vector modulation technique Electric Power Systems Research, Volume 86, May 2012, Pages 51-60

[23] *P. Palanivel S.S. Dash*, Analysis of THD and output voltage performance for cascaded multilevel inverter using carrier pulse width modulation techniques, IET Power Electron., 2011, Vol. 4, Iss. 8, pp. 951–958.

[24] *N. Farokhnia, S.H. Fathi, N. Yousefpoor, M.K. Bakhshizadeh*, Minimisation of total harmonic distortion in a cascaded multilevel inverter by regulating voltages of DC sources, IET Power Electron., 2012, Vol. 5, Iss. 1, pp. 106–114

[25] *R.V. Rao, V.J. Savsani, and D.P. Vakharia*, " Teaching–learning-based optimization: a novel method for constrained mechanical design optimization problems", Computer-Aided Design, vol 43, Iss 3, Mar 2011, pp. 303–315

[26] *R.V. Rao, V.J. Savsani, and D.P. Vakharia*, " Teaching–learning-based optimization: a novel optimization method for continuous non-linear large scale problems ", Information Sciences, vol. 183, Iss. 1, Jan 2012, pp. 1–15

[27] *Rao, R & Patel, V.* (2012). An elitist teaching-learning-based optimization algorithm for solving complex constrained optimization problems. International Journal of Industrial Engineering Computations, vol. 3, Iss. 4, 2012 pp. 535-560.