Utilizing the Cuckoo Optimization Algorithm for Selective Harmonic Elimination Strategy in the Cascaded Multilevel Inverter

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ABSTRACT

There are several procedures to solve the selective harmonic elimination (SHE) problem. In this paper, the elimination of undesired harmonics in a multilevel inverter with equal DC sources by using cuckoo evolutionary optimization method is presented. SHE is an efficient method for achieving the desired fundamental component and eliminating selection harmonics. The recently developed evolutionary optimization method named cuckoo (COA) is used to solve the nonlinear transcendental equations of SHE problem. To verify the presented method accuracy, simulation and experimental results are provided for a 7-level cascaded multi-level inverter. The feasibility and effectiveness of the proposed algorithm is evaluated with intensive simulation and experimental studies. The obtained results show that the cuckoo algorithm is more efficient than Bee algorithm (BA) and Genetic algorithm (GA) in eliminating the selective harmonics which cause the lower total harmonic distortion (THD) in the output voltage.

Keywords: Selective harmonic elimination, Multilevel inverter, Cuckoo optimization algorithm (COA).

1. INTRODUCTION

Integrating multilevel inverters into medium and high voltage industrial applications, such as motor drives [1], flexible ac transmission system (FACTS) equipment [2], HVDC [3, 4] and renewable energy systems [5], is the issue of many ongoing researches. The most advantages of multilevel inverters are derived due to stepwise waveform of output voltage. The main advantages of multilevel inverters include: High power and voltage ratings and quality, more electromagnetic compatibility, lower switching losses, higher efficiency, higher voltage capability, lower total harmonic distortion [6, 7]. Basically, there are three conventional topologies for multilevel inverters: flying capacitor [8], diode-clamped [9] and cascaded multilevel inverter with separate dc sources [10]. Among them, the cascaded multilevel inverter has received special attention due to its modularity and simplicity of control method [11, 12]. The principle operation of this inverter is usually based on synthesizing the desired output voltage waveform from several steps of voltage, which is typically obtained from DC voltage sources.

There are different power circuit topologies for multilevel converters. The most familiar power circuit topology for multilevel converters is based on the cascade connection of s number of single-phase full-bridge inverters to generate $(2s + 1)$ number of levels in the output voltage. However, from the practical point of view, it is difficult to keep equal the magnitude of separated dc sources (SDCSs) of different levels. This can be caused by the different charging and discharging time intervals of DC-side voltage sources [13]. One of the major topics in multilevel inverters is to eliminate the harmonics of output voltage. Output voltage of inverters must meet maximum THD limitations as specified in [14]. Basically, to control the output voltage and to eliminate the undesired harmonics in multilevel converters with equal DC voltage sources, there are four methods [15]. They are the fundamental frequency switching method, space vector control method [16], traditional pulse width modulation (PWM) control method and space vector PWM method [15, 17]. A large number of these methods which minimize the computational intricacy and obtaining good results have been proposed in the last 25 years [18].

Selective harmonic elimination method and THD minimization approach are other approaches which choose proper switching angles to eliminate low-order harmonics and minimize the THD of output voltage. In both cases low switching frequency and stepwise waveform of output voltage are considered. In THD minimization approach the objective is to specify the switching angles to achieve desired fundamental component with possible minimum THD [19, 20]. The objective of SHE method is to determine the switching angles so that specific lower order harmonics such as the 5th, 7th, 11th, and 13th are suppressed in the output voltage of the inverter. This method is

Manuscript received on November 12, 2013 ; revised on December 30, 2013.
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known as selective harmonic elimination (SHE) or programmed PWM techniques in technical literature [21, 22]. SHE method utilizes a set of non-linear transcendental equations as the fitness or objective function that involves many local optimal [23]. There are three procedures to solve the SHE problem, analytical approach based on resultant theory method [24], numerical iterative techniques, such as Newton-Raphson method [25] and evolutionary algorithms [26] such as genetic algorithm (GA) or particle swarm optimization (PSO) and etc. As illustrated before, SHE employs a fitness function aims to achieve the desired fundamental component and remove selective harmonics in the waveform of output voltage waveform. Various fitness functions can be defined for SHE problem [27, 28], which the purpose of all is the same.

In this paper, the COA approach is developed to deal SHE problem and determination of optimal switching angles subject to reduce THD further. Simulation and experimental results are provided for a 7-level cascaded multilevel inverter to show the validity of the proposed COA method. This paper is organized as follows. Section 2 describes the configuration of multilevel inverters, output voltage and SHE-PWM method. Section 3 describes the COA method. Section 4 defines the fitness function of SHE problem. In Sections 5 and 6, the simulation and experimental results are illustrated. Finally in Section 7 a brief conclusion is presented.

2. MULTILEVEL INVERTERS

2.1 CONFIGURATION OF THE CASCADED SEVEN-LEVEL INVERTER

Fig. 1 shows the structure of a single-phase cascaded 7-level converter topology with separate DC sources. A cascaded multilevel inverter consists of several single-phase full bridge inverters connected in series. The function of this multilevel inverter is to synthesize desired ac output voltage from several DC voltage sources connected to the individual inverter units. A cascaded multilevel inverter has advantages that have been offered in [29]. It should be pointed out that, unlike the flying-capacitor topologies and diode-clamped, isolated DC voltage sources are essential for each cell in each phase. The number of output-phase-voltage levels in a cascade multilevel inverter is $2s + 1$, where s is the number of DC voltage sources. This topology recently becomes very popular in ac power supply and adjustable speed drive applications. This inverter can avoid extra clamping diodes or voltage balancing capacitors [30]. To obtain the three-phase structure, the outputs of three single-phase cascaded inverters can be connected in Δ or Y connection.

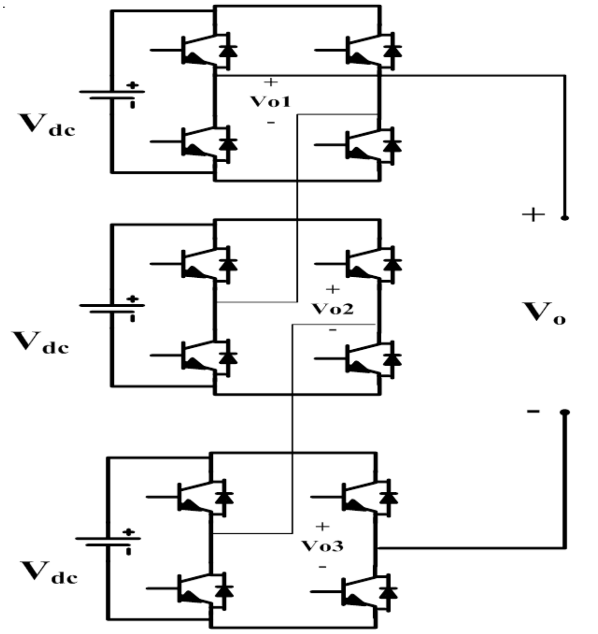


Fig.1: *Configuration of a single-phase cascaded seven-level inverter.*

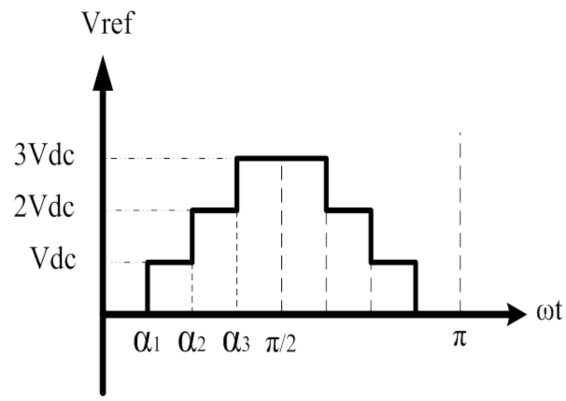


Fig.2: *The half cycle of the phase voltage of 7-level inverter.*

2.2 OUTPUT VOLTAGE OF SEVEN-LEVEL INVERTER

A half cycle of phase voltage of 7-level inverter that synthesized by several DC voltage sources is presented in Fig. 2. In this figure a_1-a_2 and a_3 are switching angles.

2.3 SELECTIVE HARMONIC ELMINATION PWM

A 7-level inverter waveform shown in Fig.2 has three variables a_1-a_2 and a_3, and voltage levels are assumed to be equal. Switching angles are limited between zero and $\pi/2$ ($0 \leq ai < \pi/2$). Because of the phase voltage waveform is an odd function, so the even order harmonics become zero. Therefore its Fourier expansion will be contained only odd harmonic components. Considering equal amplitude of all DC voltage sources, the Fourier series expansion of the output voltage waveform, shown in Fig. 2, will be written as:

$$V(\omega t) = \sum_{n=1}^{\infty} V_n sin(n\omega t) \tag{1}$$

Where V_n is the amplitude of the nth harmonic component. As illustrated before, switching angles are limited between zero and $\pi/2$ ($0 \leq$ ai $< \pi/2$). Consequently, V_n becomes:

$$f(n) = \begin{cases} \frac{4}{n\pi} V_{dc} \sum_{i=1}^{s} \cos(na_i) & \text{, n=odd} \\ 0 & \text{, n=even} \end{cases} \tag{2}$$

The purpose of SHE-PWM is to eliminate the lower order harmonics while remaining harmonics are removed by filter. In this paper, without loss of generality, a 7-level cascaded inverter is chosen as a case study to eliminate its low-order harmonics (fifth and seventh). It is needless to take the triple harmonics into consideration, since they will disappear for three-phase applications, in the line-to-line voltages. So, to satisfy fundamental harmonic and eliminate fifth and seventh harmonics, three nonlinear equations with three angles are provided as follows:

$$\begin{cases} V_1 = \frac{4}{\pi} V_{dc}(cos(a_1) + cos(a_2) + cos(a_3)) \\ V_5 = \frac{4}{5\pi} V_{dc}(cos(5a_1) + cos(5a_2) + cos(5a_3)) \\ V_7 = \frac{4}{7\pi} V_{dc}(cos(7a_1) + cos(7a_2) + cos(7a_3)) \end{cases} \tag{3}$$

In (3), V_5 and V_7 are set to zero in order to eliminate fifth and seventh harmonics, respectively. For obtaining various switching angles, a new index titled modulation index is determined to be a representative of V_1 :

$$M = \frac{V_1}{sV_{dc}} \tag{4}$$

For 7-level inverter s will be equal 3. By substituting (4) into (3), the nonlinear equation (5) can be derived and for a 7-level inverter the goal is to solve these equation.

$$\begin{aligned} M &= \frac{4}{3\pi}(cos(a_1) + cos(a_2) + cos(a_3)) \\ 0 &= (cos(5a_1) + cos(5a_2) + cos(5a_3)) \\ 0 &= (cos(7a_1) + cos(7a_2) + cos(7a_3)) \end{aligned} \tag{5}$$

Now, three optimal switching angles, namely a_1-a_2 and a_3, must be found with respect to the modulation index M.

3. PROPOSED COA METHOD

The COA is a new heuristic algorithm for global optimization searches. This optimization algorithm is inspired by the life of a bird family, called Cuckoo. Particular lifestyle of these birds and their specifications in egg laying and breeding has been the basic motivation for expansion of this new evolutionary optimization algorithm. COA similar to other heuristic algorithms such as PSO, GA, ICA, etc, starts with an initial population. The cuckoo population, in different societies, is divided into 2 types, mature cuckoos and eggs. These initial cuckoos grow and they have some eggs to lay in some host birds' nests. Among them, each cuckoo starts laying eggs randomly in some other host birds' nests within her egg laying radius (ELR). Some of these eggs which are more like to the host bird's eggs have the opportunity to grow up and become a mature cuckoo. Other eggs are detected by host birds and are destroyed. The grown eggs disclose the suitability of the nests in that area. The more eggs survive in an area, the more benefit is gained in the area. So the location in which more eggs survive will be the term that COA is going to optimize. Then they immigrate into this best habitat. Each cuckoo only flies λ% of all distance toward final destination (goal habitat) and also has a deviation of ϕ radians. These two parameters, λ and ϕ, assistance cuckoos search much more positions in all environment. For each cuckoo, λ and ϕ are defined as follows:

$$\begin{aligned} \lambda &\sim U(0,1) \\ \phi &\sim U(-\omega,\omega) \end{aligned} \tag{6}$$

Where $\lambda \sim$U(0,1) means that λ is a random number that uniformly distributed between 0 and 1. ω is a parameter that inflicts the deviation from goal habitat. When all cuckoos immigrated toward final destination and new habitats were specified, each mature cuckoo is given some eggs. Then considering the number of eggs allocated to each bird, an ELR is calculated for each cuckoo. Then new egg laying process restarts. With regard to the concept of SHE the switching angles of 7-level inverter are variables. The main steps of COA are presented in below as a pseudo-code.[31]

1. *Initialize cuckoo habitats with some random points on the fitness function*
2. *Dedicate some eggs to each cuckoo*
3. *Define ELR for each cuckoo*
4. *Let cuckoos to lay eggs inside their corresponding ELR*
5. *Kill those eggs that are recognized by host birds*
6. *Let eggs hatch and chicks grow*
7. *Evaluate the habitat of each newly grown cuckoo*
8. *Limit cuckoos maximum number in environment and kill those who live in worst habitats*
9. *Cluster cuckoos and find the best group and select goal habitat*
10. *Let new cuckoo population immigrate toward goal habitat*
11. *If stop condition is satisfied stop, if not go to 2.*

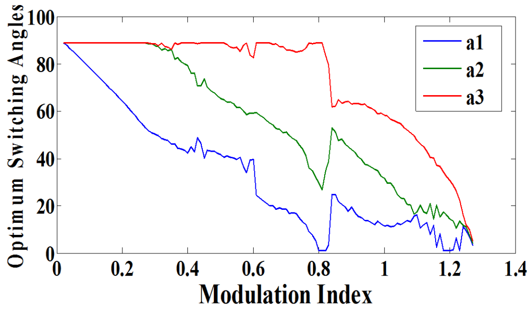
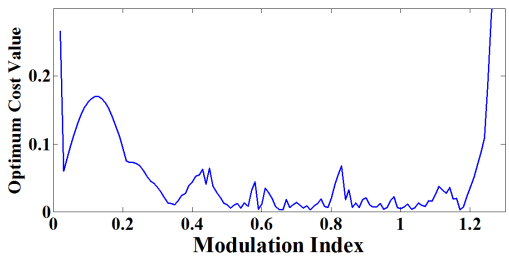
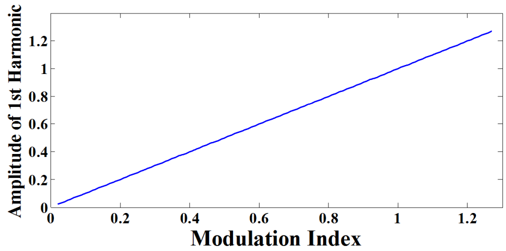


Fig.3: *Optimal switching angles (degree) versus modulation index, for fitness function (7).*



(a)



(b)

Fig.4: *(a) The optimum value of cost function (b) Normalized amplitude of fundamental harmonic.*

As illustrated before, evolutionary algorithm is an approach which can solve the SHE problem. So, we found COA to be a suitable alternative to deal with SHE problem. It is a recently developed evolutionary optimization method [32] and has good convergence in global minimum achievement in compare to other evolutionary optimization algorithms such as PSO and Genetic Algorithm (GA) [31]. Therefore, because of its high effectiveness on solving problems, it is used in multiple applications such as PID controller designing [31] or optimal placement and capacity of DG [33].

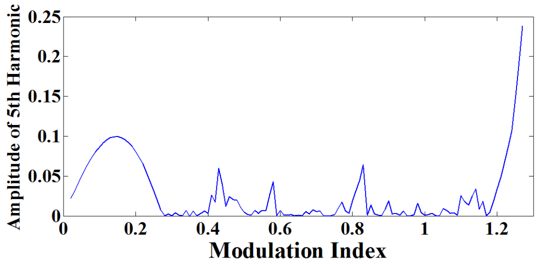
4. DEFINITION OF THE FITNESS FUNCTION FOR SHE PROBLEM

Determination of switching angles to meet the Fitness function is the main goal of proposed approach. Satisfying the desired value of fundamental component with eliminating the undesired harmonics are considered as the fitness function. In this paper COA is utilized to solve the SHE problem. The number of harmonic components which can be eliminated from the output voltage of the 2s+1 level inverter is s-1, where s is the number of separate DC voltage sources. Fitness function of seven-level inverter is considered combination of three nonlinear equations (5) that satisfy fundamental component and eliminate fifth and seventh harmonics. In (3), fundamental, fifth and seventh harmonics are achieved, respectively and will be used in (7). With previous descriptions, constructed fitness function and its restrictions are shown, respectively, in the fitness functions are defined as follows [24]:

$$100 * \left[\left| M - \frac{|V_1|}{sV_{dc}} \right| + \left(\frac{|V_5| + |V_7| + \cdots + |V_{3s-2or} V_{3s-1}|}{sV_{dc}} \right) \right] \tag{7}$$

Subject to: $0 \leq a_1 \leq a_2 \leq a_3 \leq \frac{\pi}{2}$

Where V_1 is the desired fundamental component of phase voltage and M is modulation index.



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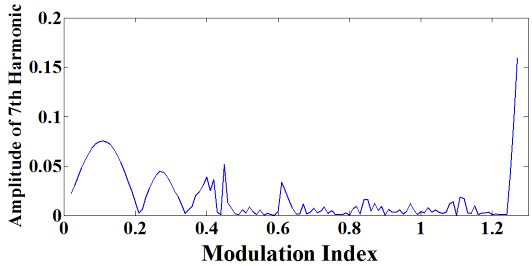
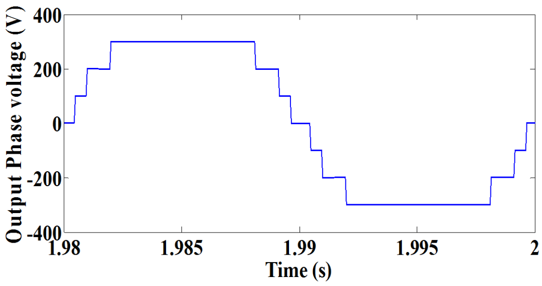


(b)

Fig.5: *(a) Normalized amplitude of 5^{th} harmonic (b) 7^{th} harmonic (V_h /3V_{dc}).*

5. SIMULATION RESULT

To validate of the simulation results for optimum switching angles, a simulation is carried out in MATLAB/SIMULINK software for a 7-level cascaded inverter. First, the COA was applied to search the optimal parameters of the SHE problem in (7), subject to its limitations. In this paper, in order to acquire the better performance of COA method, parameters in Table 1 were chosen. It should be noted that COA is run for several times, and then optimal parameters is chosen. The steps of M is considered 0.01 and after



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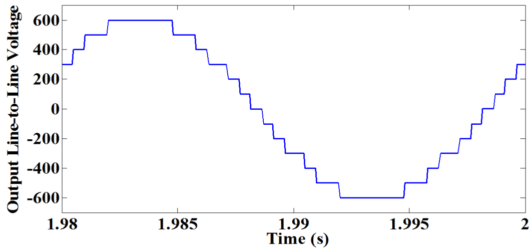

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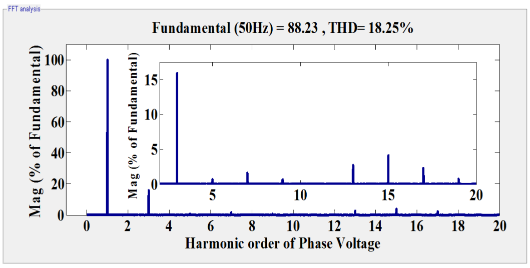

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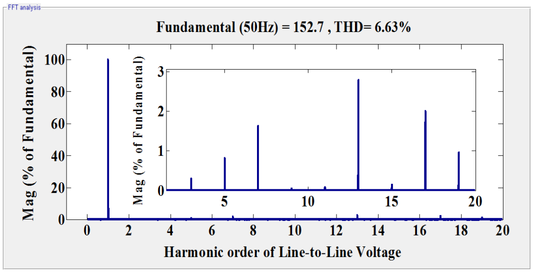


(d)

Fig.6: *Simulation results of a 7-level multilevel inverter for M = 1.17, (a) Output phase voltage (b) Output line voltage (c) FFT analysis for phase voltage (d) FFT analysis for line voltage.*

that COA is used to minimizes (7), subject to its limitations, the final optimal results (switching angles) obtained are listed in Table 2 and Table 3 for a cascaded 7-level inverter, respectively. The nominal DC voltage is considered to be 100 V. Based on cost value of fitness function or THD minimization, simulation results are presented for M= 1.17 and M=1.02.

By using COA method, the optimum switching angles based on the fitness function (7), versus modulation index, are plotted in Fig.3.

Table 1: *COA Parameters.*

Number of initial population	100
Maximum number of cuckoos that can live at the same time	35
Minimum number of eggs for each cuckoo	4
Maximum number of eggs for each cuckoo	6
Number of clusters	2
Maximum iterations	300

Table 2: *Optimal results obtained for line to line THD in cascaded 7-level inverter (V_{dc}=100v=1pu).*

THD Line%	THD Phase%	M	$a_1(°)$	$a_2(°)$	$a_3(°)$	Cost
6.63	18.25	1.17	8.08	16.97	34.96	0.003

Table 3: *Optimal results obtained for phase THD in cascaded 7-level inverter (V_{dc}=100v=1pu).*

THD Line%	THD Phase%	M	$a_1(°)$	$a_2(°)$	$a_3(°)$	Cost
9.10	12.33	1.02	10.98	29.4	56.6	0.0117

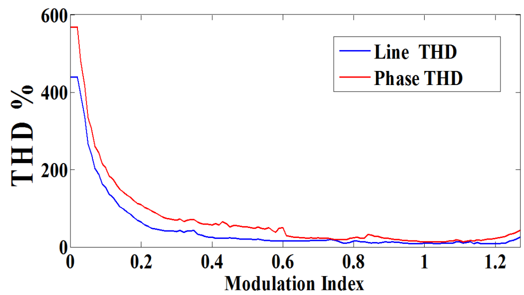


Fig.7: *Simulation results of a 7-level multilevel inverter for THD of phase and line to line output voltages.*

Fig. 4(a) represents the cost value of fitness function with respect to the modulation index. As seen from this figure, the region which has possible solutions for SHE problem, that is the cost values are almost zero. From the cost values shown in Fig. 4(a), it is obvious that the COA method is effectively able to find the optimum switching angles to suppress the undesired harmonics.

To show the effectiveness of proposed method, the fundamental harmonic and both the normalized amplitude of undesired 5^{th} and 7^{th} order of harmonics against the modulation index are illustrated in Figs. 4(b), 5(a) and 5(b), respectively. It can be seen from Figs. 4 and 5 that in some regions approximately 0.5 $\leq M \leq$ 1.2 the values of cost function are low and low-order harmonic components get nearly to zero. Out of mentioned range for M the cost function has higher values. It means that the amplitudes of low order harmonics are non zero and so the SHE problem has not any optimal solution in these regions. Also

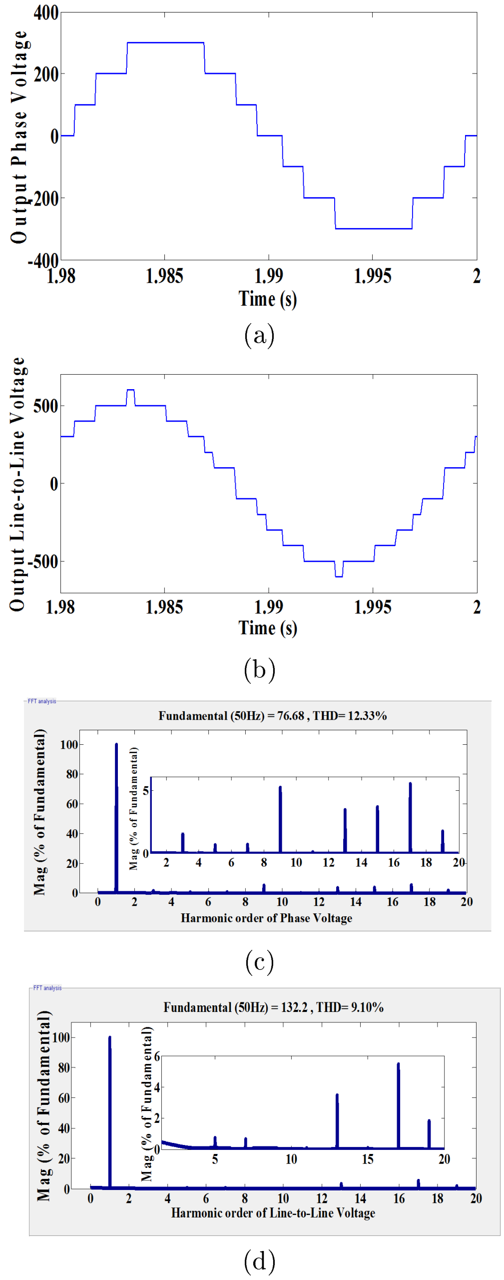


Fig.8: *Simulation results of a 7-level multilevel inverter for M = 1.02, (a) Output phase voltage (b) Output line voltage (c) FFT analysis for phase voltage (d) FFT analysis for line voltage.*

it can be seen from Fig. 4(b) that the fundamental component is mostly maintained close to the desired value.

The output phase voltage and line to line voltage waveforms for M=1.17 and the related FFT analysis are shown in Fig. 6(a)-(d), respectively.

Fig. 7 compares the phase and line to line THD of output voltages of 7-level inverter versus M. As it can be seen in Fig. 7, in this study, the minimum value of the line to line THD of output voltage occurs at M = 1.17, with a value of 6.63% and the minimum

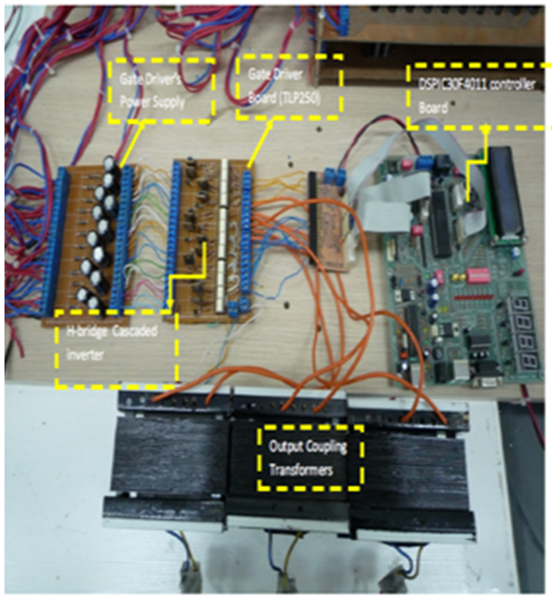


Fig.9: *Implemented prototype setup.*

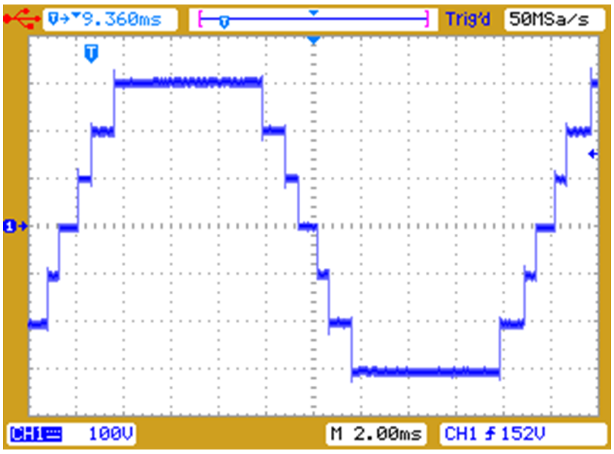
value of the phase voltage THD occurs at M = 1.02, with a value of 12.33%.

The output phase voltage and line to line voltage waveforms for M=1.02 and the related FFT analysis are shown in Fig. 8 (a)-(d), respectively.

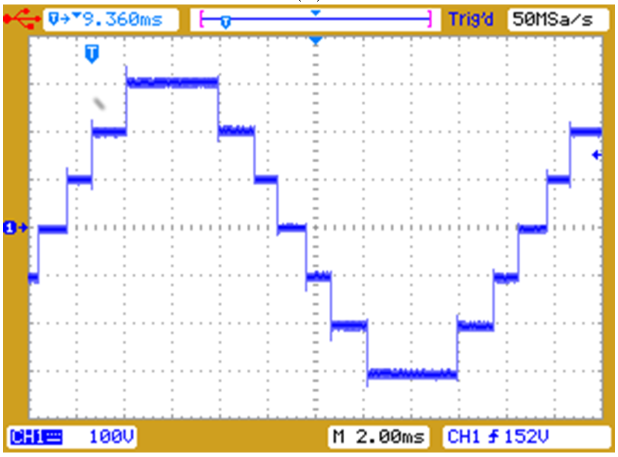
From the fast Fourier transform (FFT) analysis of the phase output voltages, it can be seen that the magnitudes of lower order 5^{th} and 7^{th} harmonics are negligible. Also it can be seen from the FFT analysis; the THD of output line voltage is very low. As the triple harmonics will not be presented in the line-to-line voltage, they are not shown in the FFT analysis of line to line voltage.

In [28] Genetic and Bee algorithms are compared to find optimal switching angles considering a proposed objective function for SHE problem. Regarding to their best results minimum line voltage THD for a 7-level inverter is 8.99%, While, in this study with considering the objective function is mostly used for SHE problem and as it seen from Figs. 4, 7 and 8, the minimum value of line voltage THD is 6.63%. The comparison of obtained results shows the accuracy and effectiveness of work done in this paper.

As known, THD is defined as the ratio of the sum of the powers of all harmonic components RMS value to the power of the fundamental frequency component RMS value. So, for a specified modulation index, voltage THD value is related to the magnitude of output voltage steps and duration of each step. So, with considering this, different values of V_{dc}, seen in Fig. 2, and also different loading conditions do not affect the THD value.



(a)



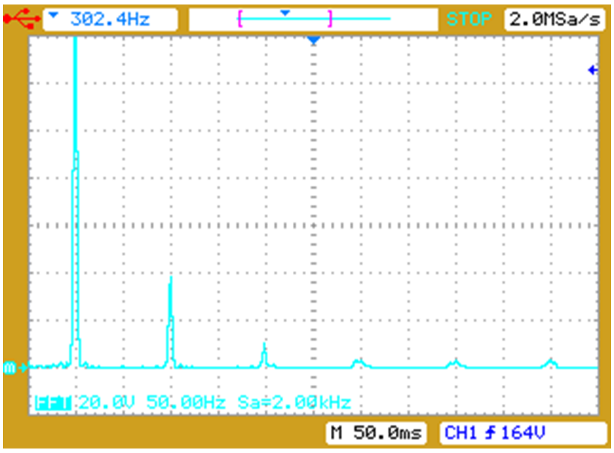
(b)

Fig.10: *Experimental results of 7-level inverter for output phase voltages for a) M=1.17, b) M=1.02.*

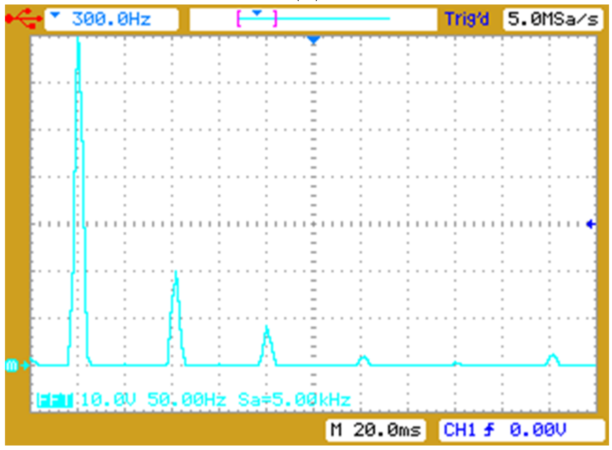
6. EXPERIMENTAL RESULT

In this paper, the results of experimental prototype of a single phase 7-level cascaded inverter are given in order to validate the obtained results. In the implemented prototype, the switching angles that listed in Tables 2 and 3 are applied. Fig. 9 shows the photograph of implemented prototype. Parameters of implemented circuit are given in Table 4. Figs. 10 and 11 describe the experimental results of implemented circuit. Figs. 10(a) and 10(b) show the output voltage of implemented 7-level cascaded inverter for M=1.17 and M=1.02, respectively. The FFT spectra of given voltages in Fig. 11 are presented in Figs. 11(a) and 11(b) respectively. It can be seen from presented simulation and experimental results that these results match saliently with simulation results.

It can be seen from Figs. 10 and 11 the obtained FFT and voltage waveforms are more similar to simulation results and the harmonic spectra of mentioned waveforms validate the implemented method efficiency.



(a)



(b)

Fig.11: *Experimental results of a 7-level inverter for FFT analysis of phase voltage.*

Table 4: *Parameters of the implemented circuit.*

Switches	IRF 840 , 500V, 8A
Gate Driver	TLP 250
Load (R-L)	175 ohm -100 mH
V_{dc}	100v

7. CONCLUSION

In this paper, the cuckoo evolutionary optimization method to solve the SHE problem is investigated. The simulation and experimental results are provided for a 7-level cascaded multi-level inverter to validate the accuracy and effectiveness of the proposed COA method for convergence objective. Based on obtained results, the presented method in this paper is compared to previous works based on BA and GA which shows that suggested method satisfying the fundamental component and eliminating the undesired low order harmonics simultaneity is well done. From the experiment we found that the percentage of THD is more in BA and GA techniques than that of COA technique.

References

[1] Rodriguez, J. Bernet, S. Bin Wu Pontt, and J.O. Kouro, S., "Multilevel voltage-source- converter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 2930-2945, Dec. 2007.

[2] Q. Song and W. Liu, "Control of a cascade STATCOM with star configuration under unbalanced conditions," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 45-58, Jan. 2009.

[3] A. O. Ibrahim, T. H. Nguyen, D.-C. Lee, and S.-C. Kim, "A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers," *IEEE Trans. Energy Convers.*, vol. 26, no. 3, Sep. 2011.

[4] C. Guo, and C. Zhao, "Supply of an entirely passive AC network through a double-in feed HVDC system," *IEEE Tran. Power Electron.*, vol. 24, no. 11, Nov. 2010.

[5] J.M Carrasco, L.G. Franquelo, J.T. Bialasiewicz, E. Galvan, R.C. PortilloGuisado, M.A.M Prats, J.I. Leon, N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: a survey," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1002-1016, Jun. 2006.

[6] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B.Wu, J. Rodriguez, M. Perez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters", *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553-2580, Aug. 2010.

[7] A. Ajami, A. Mokhberdoran, and M. R. J. Oskuee, "A new topology of multilevel voltage source inverter to minimize the number of circuit devices and maximize the number of output voltage levels," *J. Elect. Eng. Tech.*, vol. 8, no. 6, pp. 1321-1329, May 2013.

[8] A. K. Sadigh, S. H. Hosseini, M. Sabahi, and G. B. Gharehpetian, "Double flying capacitor multicell converter based on modified phase-shifted pulse width modulation," *IEEE Trans. Power Electron.*, vol. 25, no. 6, pp. 1517-1526, Jun. 2010.

[9] N. Hatti, K. Hasegawa, and H. Akagi, "A 6.6-kV transformerless motor drive using a five-level diode-clamped PWM inverter for energy savings of pumps and blowers," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 796-803, Mar. 2009.

[10] A. Nami, F. Zare, A. Ghosh, and F. Blaabjerg, "A hybrid cascade converter topology with series-connected symmetrical and asymmetrical diode clamped H-bridge cells," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 51-65, Jan. 2011.

[11] P. W. Hammond, "A new approach to enhance power quality for medium voltage AC drives," *IEEE Trans. Ind. Appl.*, vol. 33, no. 1, pp. 202-208, Jan./Feb. 1997.

[12] M. Malinowski, K. Gopakumar, J. Rodriquez, and M. Perez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197-2206, Jul. 2010.

[13] L. M. Tolbert, F. Z. Peng, T. Cunnyngham, and J. N. Chiasson, "Charge balance control schemes for cascade multilevel converter in hybrid electric vehicles", *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1058-1064, Oct. 2002.

[14] C.K. Duffey, and R.P. Stratford, "Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems", *IEEE Trans. Ind. Appl.*, vol. 25, no. 6, pp. 1025-1034, Nov./Dec. 1989.

[15] J. Rodriguez, J. Lai, and F. Peng, "Multilevel inverters: a survey of topologies, controls and applications," *IEEE Trans. Ind. Appl.*, vol. 49, no. 4, pp. 724-738, Aug. 2002.

[16] A.M. Massoud, S.J. Finney, A. Cruden, and B.W. Williams, "Mapped phase-shifted space vector modulation for multilevel voltage source inverters," *IET Electr. Power Appl.*, vol. 1, no. 4, pp. 622-636, Jul. 2007.

[17] M.T. Bina, "Generalised direct positioning approach for multilevel space vector modulation: theory and implementation," *IET Electr. Power Appl.*, vol. 1, no. 6, pp. 915-925, Nov. 2007.

[18] J. I. Leon, S. Vazquez, J. A. Sanchez, R. Portillo, L. G. Franquelo, J. M. Carrasco, and E. Dominguez, "Conventional space-vector modulation techniques versus the single-phase modulator for multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, Jul. 2010.

[19] N. Yousefpoor, S. H. Fathi, N. Farokhnia, and H. A. Abyaneh, "THD minimization applied directly on the line-to-line voltage of multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, Jan. 2012.

[20] Y. Sahali, and M. K. Fellah, "New approach for the symmetrical multilevel inverters control: Optimal minimization of the total harmonic distortion (OMTHD technique)," *Proc. IEEE ISIE*, Ajaccio, France, May 4-7, 2004.

[21] 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 1973.

[22] W. Fei, X. Du, and B. Wu, "A generalized half-wave symmetry SHE-PWM formulation for multilevel voltage inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3030-3038, Sep. 2010.

[23] H. Lou, C. Mao, J. Lu, D. Wang, and W.-J. Lee, "Pulse width modulation AC/DC converters with line current harmonics minimization and high power factor using hybrid particle swarm optimization," *IET Power Electron.*, vol. 2, no. 6, pp. 686-696, Nov. 2009.

[24] J. Chiasson, L.M. Tolbert, K. Mckenziek, and Z. Du, "Eliminating harmonics in a multilevel converter using resultant theory," *Proc. Power Electron. Specialists*, 2002, pp. 503-508.

[25] C. Silva, and J. Oyarzun, "High dynamic control of a PWM AC/DC converter using harmonic elimination," *32^{nd} Ann. Conf. IEEE Ind. Electron. Soc. (IECON 2006)*, Paris, France, 2006, pp. 2569-2574.

[26] B. Ozpinecib, L. M. Tolbert, and J.N. Chiasson, "Harmonic optimization of multilevel converters using genetic algorithms," *IEEE Power Electron. Lett.*, vol. 3, no. 3, pp. 92-95, Sep. 2005.

[27] H. Taghizadeh, and M. T. Hagh, "Harmonic elimination of cascade multilevel inverters with non-equal DC sources using particle swarm optimization," *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, Nov. 2010.

[28] A. Kavousi, B. Vahidi, R. Salehi, M. K. Bakhshizadeh, N. Farokhnia, and S. H. Fathi, "Application of the Bee algorithm for selective harmonic elimination strategy in multilevel inverters," *IEEE Trans. Power Electron.*, vol. 27, no. 4, Apr. 2012.

[29] M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Perez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197-2206, Jul. 2010.

[30] Sirisukprasert, and Siriroj, *Optimized harmonic stepped-waveform for multilevel inverter* [Online]. Available: http://www.worldcatlibraries.org

[31] R. Rajabioun, "Cuckoo optimization algorithm," *Applied Soft Computing*, vol. 1, pp. 5508-5518, Dec. 2011.

[32] H. Kahramanli, "A Modified cuckoo optimization algorithm for engineering optimization," *Int. J. Future Comput. Commun.*, vol. 1, No. 2, Aug. 2012.

[33] M. Mokhtarifard, R. Noroozian, and S. Molaei, "Determining the optimal placement and capacity of DG in intelligent distribution networks under uncertainty demands by COA," *Proc. 2^{nd} Iranian Smart Grids (ICSG)*, 2012.

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