LINE VOLTAGE THD OPTIMIZATION USING CUCKOO OPTIMIZATION ALGORITHM BASED NEURAL NETWORK TRAINED WITH IMPERIALIST COMPETITION ALGORITHM

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MTHD of output line voltage waveform in multilevel inverters is discussed in this paper. With MTHD the DC link values are set to predefined values and also the optimum switching angles are found, in order to reduce voltage THD and simultaneously generate the aimed fundamental component. In this study a method is given to find the optimum solutions using COA associated with ANNs trained with ICA. The nearest solutions provided by COA obtain a smooth data set that is desired for the ANNs training. In this study minimization of THD for constant and alterable DC sources is presented. To present the validity of the proposed approach, simulation and experimental results are provided for a test case 7-level multilevel inverter.

Keywords: THD minimization of line voltage, multilevel inverter, cuckoo optimization algorithm, imperialist competition algorithm, neural networks

1. Introduction

Multilevel inverters are extensively being used in such application as electrical drives and flexible AC transmission systems (FACTs) devices [1-6]. The main characteristic of multilevel inverters is their stepwise output voltage waveform which causes some advantages compared to the traditional two-level inverters. Higher power quality, better electromagnetic compatibility, lower switching losses and higher voltage capability [7-10] are the main advantages of multilevel inverters. The main configurations of multilevel inverters are classified into three types, those are, the flying capacitor [11, 12], diode clamped [13, 14], and cascaded multilevel inverters [15]. Among the multilevel inverter configurations, the diode-clamped multilevel inverter (DCMLI) is widely

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accepted for applications in high-power drives and utility systems. It possesses some of the desirable features like the following: 1) the dc capacitors can be easily recharged as a group; 2) switching control is easiest; and 3) the protection circuit required is least complex among the multilevel inverters, etc [16-18]. The subject of many ongoing studies is improving the output waveform of multilevel inverters quality. The switching strategies of the multilevel inverters are separated into three main collections: space vector modulation, minimization of the total harmonic distortion, selective harmonic elimination, sinusoidal pulse width modulation and pulse width modulation (SHEPWM) [19–24]. THD minimization strategy is an efficient method for minimizing all harmonic components and also providing the fundamental component. In THD minimization, obtaining the possible minimum THD with achieving the desired amplitude of fundamental component is aimed, whereas in selective harmonic elimination approach some low-order harmonics are minimized or eliminated. THD minimization method is generally applied to phase voltage waveform of multilevel inverters. It should be noted that minimum phase voltage THD does not lead to minimum line to line voltage THD. But in three phase applications from the load point of view, Line voltage has got more importance than the phase voltage. In [20] THD minimization is implemented on line voltage waveform of output. OMTHD technique is based on optimal minimization of THD [25], which the switching angles are determined to minimize the THD of the voltage waveform. MTHD is suitable for some cases e.g. multilevel electrical drives and flexible AC transmission systems devices such as multilevel static var compensator, multilevel unified power quality conditioner and multilevel unified power flow controller, where DC link voltages are altering. Outcomes confirm the effectiveness of MTHD in minimizing THD, when it is compared with the case of a multilevel inverter with constant DC sources. A new approach is proposed in this paper which is more efficient than previous works in minimizing THD. So, this paper has two steps: COA is developed to deal with the MTHD problem. The nearest solution providing a smooth data set that is most wanted for the Artificial neural networks (ANN) training, is found by COA. Then, with the previous data set, the ANN will be trained to provide the set of solutions for each modulation index value. ANNs training is done by ICA. ANNs are non-liner data driven self adaptive approach in contrast with traditional model. Neural networks map the relationship between input and output data without prior knowledge of the process. An ANN is generally clarified by three types of parameters: The interconnection pattern between different layers of neurons, the learning process for updating the weights of the interconnections and the activation function that converts a neuron's weighted input to its output activation. The process of tuning their inner parameters named weights from data called learning or the training process. Weights between the neurons make the global minimum of error function. Solving the estimated answer to inputs that were not during training constitutes the ability of ANNs. These features make ANNs suitable for problems commonly encountered in power electronics such as fault detection [26], harmonic diagnostic [27] and Fault diagnostic [28]. To present the validity of the proposed approach, simulation and experimental results are provided for a test case 7-level multilevel inverter.

2. Multilevel inverters output voltage

A half cycle of a typical waveform of the reference phase voltage of a 7-level inverter composed by three DC links is shown in Fig. 1.

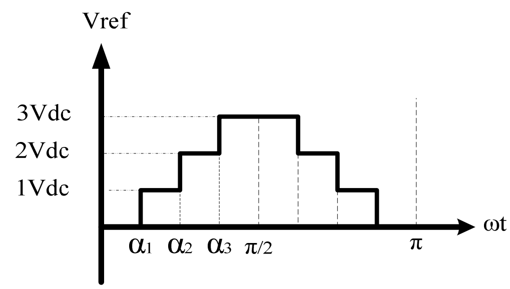


Fig. 1 Half cycle of the reference phase voltage of a 7-level inverter with constant DC sources

Fig. 2 shows a half cycle of a typical staircase waveform of the reference phase voltage of 7-level inverter synthesized by alterable DC sources.
Fourier analysis is used to determining the instantaneous value of reference phase voltage. Thus Fourier analysis is applied to Fig.1 and Fig. 2 and the following term is achieved.

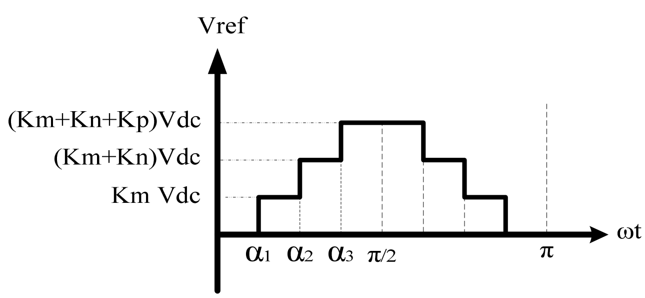


Fig. 2 Half cycle of the reference phase voltage of a 7-level inverter with alterable DC source

It must be noted that, the presented waveform of V_a is odd function, it includes odd-order harmonics only (for odd n).

$$V_a = \sum_{n=1}^{\infty} \frac{4}{n\pi} V_{dc} sin(\frac{n\pi}{2})(cos(na_1) + cos(na_2) + cos(na_3)) Sin(nwt) \tag{1}$$

$$V_a = \sum_{n=1}^{\infty} \frac{4}{n\pi} V_{dc} sin(\frac{n\pi}{2})(\mathrm{K_m} cos(na_1) + \mathrm{K_n} cos(na_2) + \mathrm{K_p} cos(na_3)) Sin(nwt) \tag{2}$$

The equation (1) is for Fig. 1 and the equation (2) is related to Fig. 2. Regardless of the phase voltage, for Line-to-line voltage of multilevel inverters there is no forthright way to identify the RMS value of the waveform since its form is not unique and varies if the switching angles change. Therefore, there is no possibility to find a unique formula for RMS value of line-to-line voltage THD for all switching angles. The only way to have RMS value of line voltage required to work out THD, is to establish it from phase voltage instantaneous values. The staircase waveform of line voltage can be reached by subtracting any phase voltage from another one since all three phase voltages have the same waveform with a phase separation one-third cycle (2pi/3):

$$V_{ab}(\omega t) = V_a(\omega t) - V_b(\omega t) \tag{3}$$

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

Now, for any set of switching angles a specific waveform for line voltage is defined. Thus, by integrating the waveforms rectangular segment the line voltage RMS value can be calculated. As a result of symmetry, amplitude of fundamental component of phase voltages is equal and has 2pi/3 difference in their phases. Consequently the RMS value of the line voltage fundamental component will 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:

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

$$V_{l1} = \frac{4\sqrt{3}}{3\pi}(\mathrm{K_m}\cos(a_1) + \mathrm{K_n}\cos(a_2) + \mathrm{K_p}\cos(a_3)) \tag{6}$$

The equation (5) is for Fig. 1 and the equation (6) is related to Fig. 2

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. Finally, calculating the line THD is available with following equation

$$THD_{line} = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^{\,2}}{V_1^{\,2}}} = \sqrt{\left(\frac{(V_l^{\,2})_{rms}}{(V_{l_1})_{rms}}\right)^2 - 1} \tag{7}$$

3. THD Minimization

In the objective function the target is to satisfy the desired value of fundamental component while having possible minimum THD. To meet objective function, suitable switching angles and DC link voltages must be optimized. The objective function is defined as follows:

$$objective: \left|V_{l1}^{\,*} - V_{l1}\right| + THD_{line} \tag{8}$$

Where $V_{l1}^{\,*}$is modulation index, varies from zero to$\frac{4\sqrt{3}}{\pi}$. $V_{l1}$and THD_{line} are substituted from the corresponding equations obtained in the previous section. The obtained switching angles which are the solutions of objective function, stated before, must gratify in the following basic constraint:

$$0 \le a_1 \le a_2 \le a_3 \le \frac{\pi}{2} \tag{9}$$

The equation (9) is for both waveforms, shown in Fig. 1.and Fig. 2. For the waveform represented in Fig. 2 another constraint, equation (10), must be defined. The amplitude of DC voltage sources must gratify in the following basic constraint:

$$0 \le K_m, K_n, K_p \le 1 \tag{10}$$

4. 1 Cuckoo Optimization Algorithm

Given that THD minimization is an optimization problem, COA is found to be an appropriate alternative in this regard. 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 two 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

$$\lambda \sim U(0,1) \quad (11)$$

$$\phi \sim U(-\omega,\omega) \quad (12)$$

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:
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. The main steps of COA are presented in below as a pseudo-code.

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.

This optimization algorithm employed in many applications to solve the defined problems because of its higher efficiency means good convergence and global minimum achievement. In this paper COA is applied to solve the aforementioned objective functions and find smooth data set for training the ANNs.

4. 2 Neural network structure

The computational models that were enthuse by the biological neurons named Artificial Neural Networks. Neural networks are classically structured in layers. Layers are made up of a number of interconnected nodes. Each node contains an activation function. The first layer has input neurons which send data via weights to the second layer of neurons, and then via more weights to the third layer of output neurons. More complex systems will have more layers of neurons with some having increased layers of input neurons and output neurons. The synapses store parameters called "weights" that manipulate the data in the calculations. A layer that linked between inputs and out layer called hidden layers. ANN is typically defined by three types of parameters:

1. The interconnection pattern between the different layers of neurons

2. The learning process for updating the weights of the interconnections

3. The activation function that converts a neuron's weighted input to its output activation.

The most challenge in neural networks is the possibility of learning. ANNs contain some form of learning rule which modifies the weights of the connections according to the input patterns. Convergence in general depends on a number of factors: Firstly, there may exist many local minima. This depends on the cost function and the model. Secondly, the optimization method used might not be guaranteed to converge when far away from a local minimum. If, learning algorithm are selected appropriately the resulting ANN can be extremely robust. Fig. 3 shows the structure of ANNs.

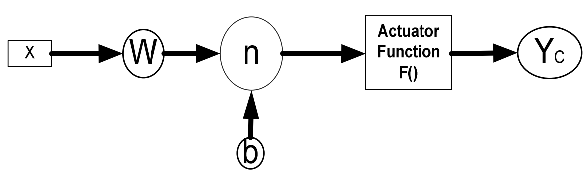


Fig. 3 Typical ANNs structure

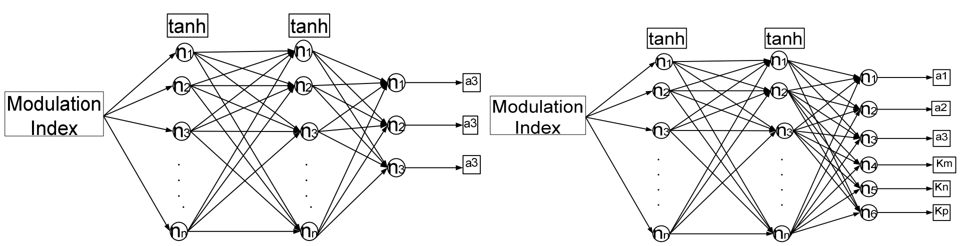
ω is neural network weight that updated at any iteration of learning to achieve the minimum cost. n illustrates the neurons. X is input pattern. Y_c is output result calculated by neural network. $F(.)$ is the actuator function. In this paper the actuator function for the entire layer is tanh.

$$n = \omega \times X + b \tag{13}$$

$$Y_c = F(\mathrm{n}) \tag{14}$$

$$MSE = \sum_{i=1}^{n} (Y - Y_C) \tag{15}$$

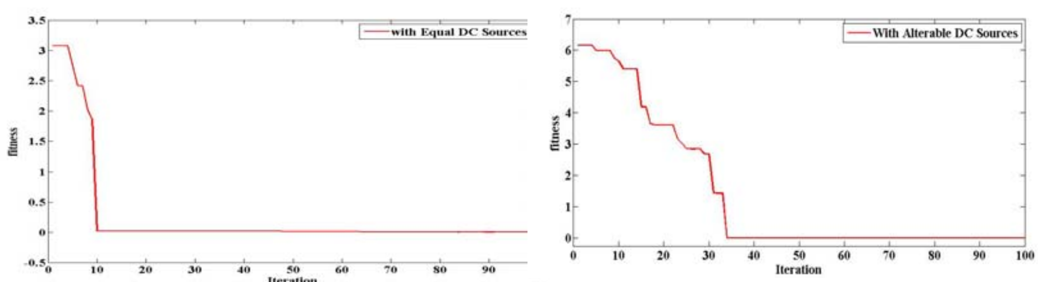
In literatures, several methods have been implemented to find the ANNs parameters in order to find the global minimum and overcome the problem of local minima. In this regards the defined cost function must be minimized. In this manner the MSE (Minimum Square Error) function is treated as a cost function for ANN training. The real output is Y and the calculated output via neural network is mentioned as Y_c. The ω and b are considered as ANN's parameters which must be evaluated. The optimization method used to determine weight adjustments has a large influence on the performance of ANNs. Due to important of the training step, many methods such as back propagation [30], and particle swarm optimization algorithm (PSO) [31] and ICA [32] were used to find out the ANN parameters. As mentioned before, ANNs training process is an optimization problem. In order to find the optimum weights of ANNs, requested in ANNs structure ICA is used. In the optimization process, at first the related cost function of weights optimization should be extracted. Thus to product the Y_c at the last layer the variable of the each layer must be extracted. So, to find the solution, a row vector of real numbers of variable is defined. This variable is one of the population matrix rows which contain neural network weights and biases. After the network creation, the assessment phase based on different values of variables is started. As a final point, assuming a weight function, by adding input values, the output is simulated; afterward, the MSE is obtained by subtracting the network output and the actual output and is stored as a cost function. Finding optimized value of the variables by ICA, MSE cost function values comes zero or close to zero.



(a) (b)

Fig. 4 the structure of ANNs, a) constant DC sources, b) alterable DC sources

All the weights in a network are represented by a group of real numbers. Fig (4-a) shows, modulation index and switching angles are the entrance and output of the network respectively. Cuckoo algorithm found the modulation index and switching angles. The ICA must found the parameters of the network to connect the input to the output and product the correct output. These parameters are weights and biases of each layer. This process is important and need more attention to obtain the best result. This application is because of high convergence speed and the ability of ICA in optimization of the MSE defined in the MLP network. In this study, modulation index is the input of ANNs for both mentioned cases, inverters with constant and alterable DC links. The outputs are switching angles for a case with constant DC sources, shown in Fig 3 (a). The switching angles with K_m, K_n *and* K_p for a case with alterable DC sources are the outputs of ANNs shown in Fig 4 (b). Fig. 5 shows the minimization process of fitness function for both methods obtained by ICA versus iteration number. An important point of an ANN that made it appropriate for this problem is its flexibility work with the non-linear nature of the problem. Although the data set presented to the ANN is not complete and not all combinations were obtained by the COA, the ANN has flexibility enough to interpolate and extrapolate the results. In simple words, the suggested approach can be implemented as following: Firstly, the defined objective functions are minimized using COA. The obtained optimum solutions versus modulation index are gathered in look up table. These solutions are switching angles for a case with constant DC sources and are switching angles and the value of DC links for a case with alterable DC sources. The provided solutions do not cover the whole ranges of 0 to 1 of modulation index. Because optimization processes for whole ranges are highly time consuming. This is the main problem of optimization process. Therefore, a step was defined for modulation index.



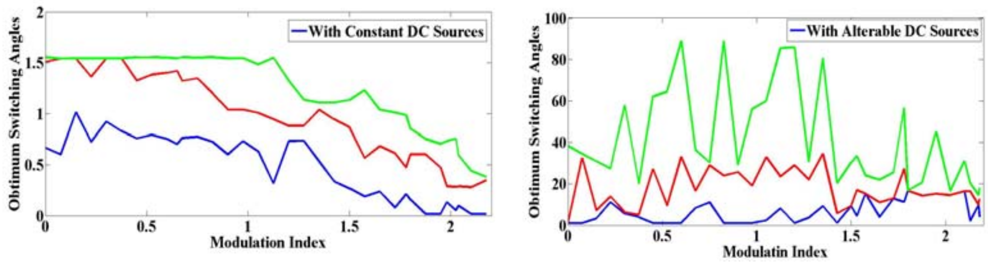
(a) (b)

Fig. 5 ICA Minimization process for a case, a) constant DC Sources, b) Alterable DC Sources

The lack of any modulation index can be overcome by the use of ANN. As known, the specific load voltage is pointed by its modulation index. When the requested modulation index by the load is not in look up table, the control unit detects it and puts the ANN into practice. ANNs are applied to the data set of look up table. So resulting, optimum solutions for that modulation index can be obtained. In this regards, any values of voltage amplitude with minimum THD can be generated. These voltage amplitudes can be the ones not defined previously in look up table found by optimization process.

5. Simulation Results

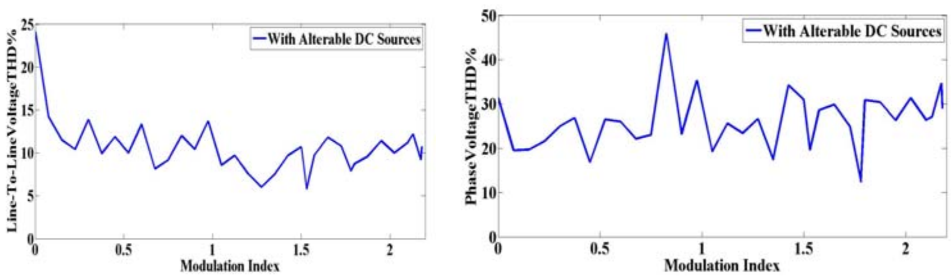
In this paper, THD minimization method is directly applied to the line voltage of the inverter. The obtained optimum switching angles (degree) for both mentioned cases versus the modulation index are plotted in Fig.6 (a) and (b), respectively



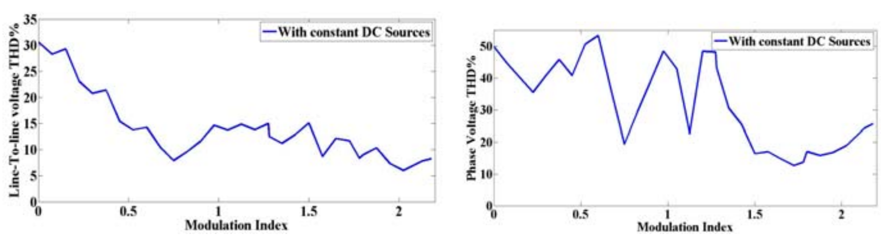
(a) (b)

Fig. 6 The obtained switching angles per modulation index, a) related to Fig. 1, b) related to Fig. 2

Fig. 7 shows clearly the THD values of line-to-line voltage and phase voltage versus modulation index.



a



b

Fig. 7 THD values versus modulation index, a) related to Fig. 1, b) related to Fig.2

The obtained amplitude of DC sources is given in Fig. 8, related to Fig. 2. The variance between line THD and phase THD demonstrates that there is no definite respect between phase voltage THD and line-to-line voltage THD and there is no necessity to phase voltage lead to lower THD value while minimum value of the line-to-line voltage THD is obtained.

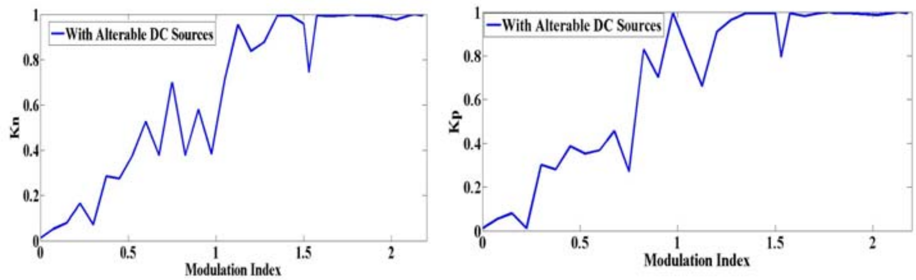


Fig. 8 The obtained results for the values of DC sources versus modulation index related to Fig. 2

Fig.8 compares the simulated values for line voltage THD in both cases. It depicts a considerable improvement when the THD minimization is directly applied to the line voltage with alterable DC sources. It's obvious that line voltage THD values for a case with alterable DC sources are always lower than the THD values when constant DC sources are mentioned. Table I and II show the optimum switching angles (degree) and the simulated values for Line and phase voltage THD, for the modulation indexes where the lower line voltage THD is obtained.

Table I

(Fig.1)

				Phase THD%	Line-To-Line THD%
2.04	5.4	16.7	34.4	18.88	5.84

Table II

(Fig.2)

							Phase THD%	Line-To-Line THD%
1.53	4.5	17.1	33.4	0.745	0.795	0.69	19.2	5.79

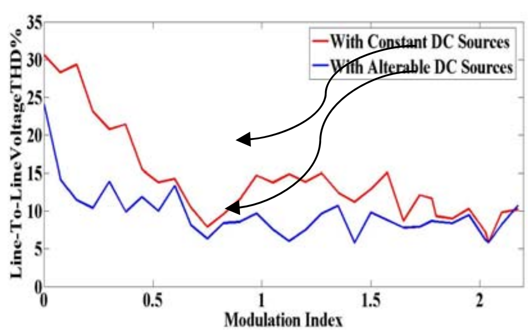
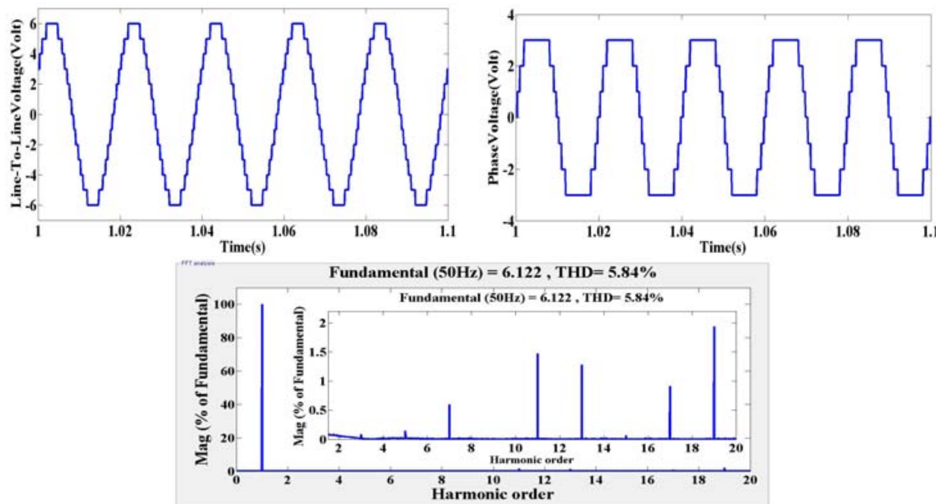
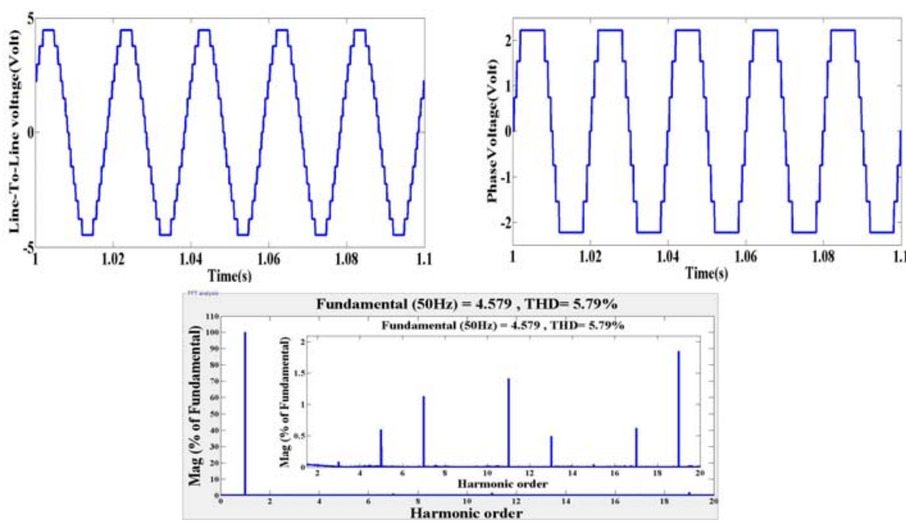


Fig. 9 The comparison between Line-to-Line voltage THD values obtained from both cases

It's seen from the above tables, the least Line-to- Line voltage THD value from the proposed scheme is lower than the THD values given in [27] using GA to solve MTHD problem. So, this comparison validates the efficiency of applied scheme in this paper. As a case study the related phase voltage and Line-To-Line voltage for the V_{l1}^{*} values, given in Table I and II, and also harmonic content of them are shown in Fig. 10.



a)



b)

Fig. 10 phase voltage, Line-To-Line voltage and the harmonic spectra of Line voltage, a) connected to Fig. 1 and $V_{l1}^{*} = 2.038$ b) connected to Fig. 2 and $V_{l1}^{*} = 1.278$; where $V_{dc} = 1^{v}$

As it is shown in Fig. 10, the phase and line voltage can be generated in a correct form which validates the accuracy of obtained solutions. Also, the harmonic content of line voltages are detailed which shows that with proposed scheme the obtained value for Line voltage THD is lower when alterable DC sources are used.

6. Experimental result

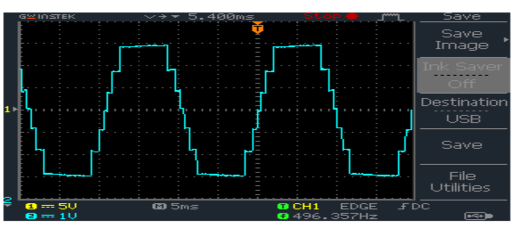
The experimental studies are carried out to validate the computational results and good performance for both method pointed up before. An experimental two phase prototype of a three-phase seven level Y-connected Diode-Clamped inverter is implemented.

Table III

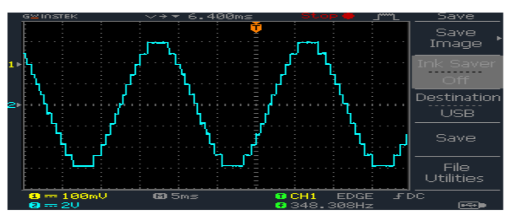
Value of parameters in implemented inverter

DC voltage sources In symmetric case	Vdc=10 V
Type of switch	IRFP450
Type of IGBT Driver	TLP250

Fig. 11 shows the obtained results from the experimental studies. Fig. 11 (a)-(b) depict the first case which points to multilevel inverter with constant DC sources and the switching pattern. And Fig. 11 (c)-(d) shows the second case which shows operation of inverter with alterable DC sources and the switching pattern. The measured THD values from experimental prototype for both methods with the data given in Table I and Table II are 5.9 and 5.87, respectively. The defined experimental results show the accuracy of obtained results and practicability of process and also cope nearly with simulation results.

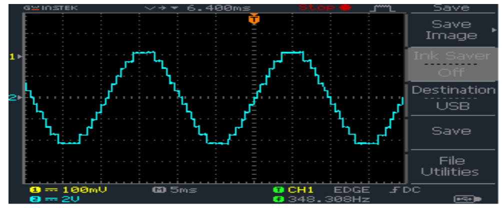


a



b

c



d

Fig. 11 a) output phase voltage, b) output line voltage; with constant dc sources with the switching pattern given in table i (1*10 volt/div); c) output phase voltage, d) output line voltage; with alterable dc sources with the switching pattern given in table ii (1*10 volt/div)

7. Conclusions

In general, the THD minimization is applied on phase voltage because of its plain waveform and ease of formulation. But getting the lower possible line voltage THD in three phase applications is considered as an important issue because the line voltage is more essential and is of the main concern of load point of view in three phase applications. This paper has presented an advanced procedure of THD minimization (MTHD) which is directly applied to the line-to-line voltage. MTHD is an appropriated method to improve the quality of output voltage waveform for some cases e.g. multilevel electrical drives and flexible AC transmission systems devices such as multilevel static var compensator, multilevel unified power quality conditioner and multilevel unified power flow controller, where DC link voltages are altering.

Optimum solutions initially are found by COA and then to expand the optimum solutions for all range of modulation index the obtained solutions are given to neural network which is trained by ICA to calculate the optimum solutions in real-time.

Finally, the simulation and experimental results demonstrated the proposed approach efficiency in THD minimization.

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