



Application of Harmony Search algorithm with Neural Networks Solving MTHD Problem in Multilevel inverter with Alterable DC links

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Abstract: Minimization of Total Harmonic Distortion (MTHD) for the line-to-line output voltage of multilevel inverters has been studied in this work. Harmony Search (HS) Algorithm with artificial neural networks (ANN) has been employed to solve the aforementioned problem with considering constant and alterable DC sources in order to minimize Total Harmonic Distortion more efficiently. The nearest solutions provided by HSA obtain a smooth data set that is desired for the neural network training. MTHD is suitable for some cases, e.g. multilevel electrical drives and flexible AC transmission system devices such as multilevel static VAR compensator, multilevel unified power quality conditioner and multilevel unified power flow controller, where DC link voltages are altering. MTHD not only optimizes the switching angles, also finds the optimum values for DC links. In this work THD minimization with employing both constant and alterable DC sources has been researched and compared with each other. Also a comparison is made with a recently published paper using GA, which validates that the proposed scheme is more efficient in this regard. Numerical results for a test case, seven-level inverter, reveal that the presented method is feasible.

Keywords: THD Minimization, Harmony Search Algorithm (HSA), Line-To-Line voltage of multilevel inverter, Artificial Neural Networks

1. Introduction

In the past years, many power electronic engineers have focused on multilevel inverters. Better electromagnetic compatibility (EMC), lower of dv/dt stresses, lower total harmonic distortion (THD) of input and output due to an increase in output voltage levels, lower rating of power semiconductor, lower switching losses and higher power quality are some of the main advantages of multilevel inverters over conventional two-level ones [1, 2]. Multilevel inverters are mainly classified into three configurations: flying capacitor multilevel inverters [3, 4], Diode-Clamped multilevel inverters [5-7] and Cascade H-Bridge multilevel inverters (CHML) [8]. From the aspect of DC source values, multilevel inverters are divided into two groups. If all the DC voltage sources have equal values, the multilevel inverter is called the symmetric topology; Otherwise, it is called asymmetric. Asymmetric multilevel inverters create more number of voltage levels for a particular number of switches. DC voltage source can be capacitors, batteries and renewable energy sources. Multilevel inverters have a stepwise output voltage waveform which is synthesized by several DC voltage sources [9]. If the number of steps are increased, multilevel inverter can generate a near sinusoidal output voltage and reduce the THD of output voltage. However, voltage-unbalance problems, circuit layout and voltage clamping, limit the number of possible steps. Consequently, the reduction of THD is a vital issue in designing an effective and efficient multilevel inverter. Hence, the subject of many recent papers is improving the output waveform quality by minimizing the THD. In order to qualify the output waveform of the multilevel inverters several switching strategies have been proposed which are: space vector modulation, minimization of the total harmonic distortion, selective harmonic elimination, sinusoidal pulse width modulation and pulse width modulation (SHEPWM) [10-17]. In selective harmonic elimination strategy some

low order harmonics are eliminated and the desired amplitude of fundamental component is achieved. But in THD minimization method all harmonic components are minimized to the least possible value while providing the predefined fundamental component. OMTHD is a strategy based on optimal minimization of THD [18]. With OMTHD the switching angles are determined in a way that THD of the voltage waveform will be the minimum. Phase voltage has unique waveform and simpler calculation. So THD minimization method is generally applied to phase voltage waveform of multilevel inverter. It should be noted that the 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 [19] THD minimization is implemented on the line voltage waveform of output. In [20] a switching strategy has been developed based on minimization of total harmonic distortion (MTHD). 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. THD minimization for alterable DC sources is more efficient than the case with constant DC sources. Given that MTHD is an optimization problem, intelligent algorithm is found to be an appropriate alternative in this regard. As mentioned before, there are some works in THD minimization. The new approach proposed in this paper is more efficient than previous works in minimizing THD. So, this study has two steps: initially Harmony Search Algorithm is developed to deal with the THD minimization problem. The nearest solution providing a smooth data set that is most wanted for the neural network training will be found by HSA. Then, with the previous data set, the artificial neural networks (ANN) will be trained to provide the set of solutions for each modulation index value. ANNs are non-linear data driven, self-adaptive approach in contrast with traditional model. ANNs 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 the error function. Solving the estimated answers of inputs that were not found during training is the ability of ANNs. These features make ANNs suitable for problems commonly encountered in power electronics such as fault detection [21], harmonic diagnostic [22] and Fault diagnostic [23]. The main contribution of this paper is to propose a novel approach regarding to reduce the THD more efficiently. In this paper, two cases are determined in the cost function; a case with constant DC sources and a case with alterable DC sources. Comparing them shows the effectiveness of the case with alterable DC sources in minimizing the THD value. Also the obtained results are compared with a recently published paper using GA to solve MTHD. The comparison validates the effectiveness of the proposed scheme in MTHD problem which causes a lower THD for both cases with alterable and constant DC sources. The rest of this paper is organized as follows: The output voltage of multilevel inverter is discussed in section II. Section III gives more details about THD minimization. Section IV provides a description of Harmony Search Algorithm. Section V involves the neural network structures. VI and VII specified for simulation and experimental results. And finally conclusion is presented in Section VIII.

2. Multilevel Inverter's Output Voltage

Figure 1 (a)-(b) exhibits a typical positive half cycle waveform of the reference phase voltage of a seven-level inverter composed by three DC links. Figure 1 (a) is when DC sources have constant values and Figure 1 (b) shows the waveform when it is synthesized by adjustable DC sources.

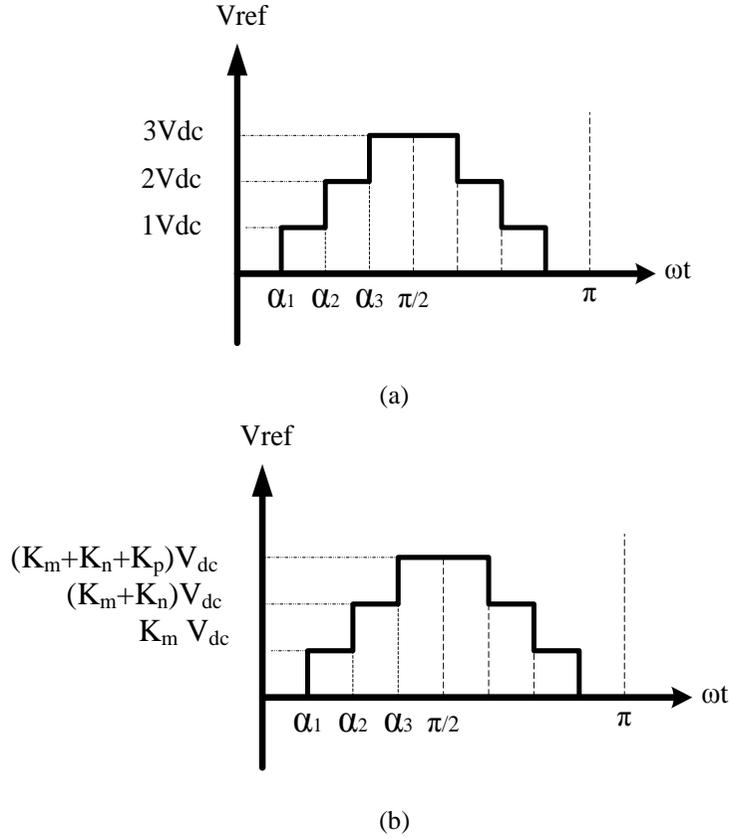


Figure 1. Half cycle of the reference phase voltage of a 7-level inverter (a) with constant DC sources (b) with alterable DC sources

To detail a complete cycle of the shown waveforms all switching angles, $\alpha_1 - \alpha_3$ are required. With regards to Figure 1 (a) and Figure 1 (b), the voltage waveforms, V_a , can be proved in terms of step function $u(\omega t)$:

For positive half of the waveform we have:

$$V_{ap} = \sum_{i=1}^{i=3} V_{dc} (u(\omega t - \alpha_i)) - \sum_{i=1}^{i=3} V_{dc} (u(\omega t - \pi + \alpha_{4-i})) \quad 0 < \omega t < \pi \quad (1)$$

$$V_{ap} = K_m u(\omega t - \alpha_1) + K_n u(\omega t - \alpha_2) + K_p u(\omega t - \alpha_3) - K_p u(\omega t - \pi + \alpha_1) - K_n u(\omega t - \pi + \alpha_2) - K_m u(\omega t - \pi + \alpha_3) \quad 0 < \omega t < \pi \quad (2)$$

The equations (1) and (2) are related to Figure 1 (a) and Figure 1 (b), respectively. The negative half is in the reverse direction and lagging π radians for V_{ap} .

$$V_{an} = -V_{ap}(\omega t - \pi) \quad \pi < \omega t < 2\pi \quad (3)$$

Thus the sum of equations (1) and (2) provides the reference phase voltage:

$$V_a = V_{an} + V_{ap} \quad (4)$$

To identify instantaneous values of reference phase voltage, Fourier analysis is used. Hence Fourier analysis is implemented to V_a and the following term is reached. The shown waveform of V_a is an odd function and it only includes odd order harmonics ($n = 2k \pm 1$).

$$V_a = \sum_{n=1}^{\infty} \frac{4}{n\pi} V_{dc} \sin\left(\frac{n\pi}{2}\right) (\cos(na_1) + \cos(na_2) + \cos(na_3)) \sin(n\omega t) \quad (5)$$

$$V_a = \sum_{n=1}^{\infty} \frac{4}{n\pi} V_{dc} \sin\left(\frac{n\pi}{2}\right) (K_m \cos(na_1) + K_n \cos(na_2) + K_p \cos(na_3)) \sin(n\omega t) \quad (6)$$

The equation (5) and the equation (6) are associated with Figure 1(a) and Figure 1 (b), respectively.

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 ($2\pi/3$):

$$V_{ab}(\omega t) = V_a(\omega t) - V_b(\omega t) \quad (7)$$

$$V_{ab}(\omega t) = V_a(\omega t) - V_a\left(\omega t - \frac{2\pi}{3}\right) \quad (8)$$

Now, for any set of switching angles a specific waveform for line voltage is defined. Thus, by integrating waveforms of the 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 $2\pi/3$ 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:

$$V_{l1} = \frac{4\sqrt{3}}{3\pi} (\cos(a_1) + \cos(a_2) + \cos(a_3)) \quad (9)$$

$$V_{l1} = \frac{4\sqrt{3}}{3\pi} (K_m \cos(a_1) + K_n \cos(a_2) + K_p \cos(a_3)) \quad (10)$$

The equations (9) and (10) are related to Figure 1 and Figure 2, respectively. THD is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Eventually, evaluation of the line THD is available by following equation:

$$THD_{line} = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{V_1^2}} = \sqrt{\left(\frac{(V_l)_{rms}}{(V_l)_{rms}}\right)^2 - 1} \quad (11)$$

3. THD Minimization

In the objective function the target is to satisfy the desired value of the fundamental component while having possible minimum THD. To meet objective function, suitable switching angles and DC link voltages must be determined. In this paper HSA is employed to solve the defined problem. HSA is a new developed optimization method which was sparked by the improvisation of Jazz musicians. HS is a strategy which is employed in many applications to solve the defined problem because of its high efficiency means good convergence and global minimum achievement. The objective function is defined as follows:

$$\text{Objective : } \quad \left| V_{11}^* - V_{11} \right| + THD_{line} \quad (12)$$

Where the modulation index (V_{11}^*) varies from zero to $\frac{4\sqrt{3}}{\pi}$. V_{11} and THD_{line} are substituted from the corresponding equations achieved in the previous section. The first part of the stated objective function $\left| V_{11}^* - V_{11} \right|$ is the absolute value of error in adjusting the fundamental harmonic. By minimizing the objective function, the optimum solutions will be obtained. The obtained switching angles must satisfy the following fundamental constraint:

$$0 \leq a_1 \leq a_2 \leq a_3 \leq \frac{\pi}{2} \quad (13)$$

The equation (13) relates to both waveforms in Figure 1.

The following basic constraint must be considered for the amplitude of DC voltage sources for the waveform shown in Figure 1(b):

$$0 \leq K_m, K_n, K_p \leq 1 \quad (14)$$

Generally the THD minimization process is implemented in phase voltage more than line voltage due to phase voltage's simpler formulation. However, in this study THD minimization is applied to the line-to-line voltage of the 7-level inverter with constant and alterable DC sources.

4. Harmony Search Algorithm (HSA)

Harmony Search was sparked by the improvisation of Jazz musicians [24]. Specifically, the process by which the musicians (who have never played together before) quickly refine their individual improvisation through adjusting the pitches of their instruments resulting in a pleasing harmony. HS is a high performance meta-heuristic algorithm which uses stochastic random search instead of a gradient search. Simple concept, few parameters to adjust, and easy implementation make HS as the major competitor of other evolutionary algorithms. In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make a good harmony, that experience is stored in each player's memory, and the possibility to make a good harmony is increased next time. Following statements represents the optimization procedure of the HS algorithm, which contains steps

1–5, as follows:

Step 1. Initialize the problem and algorithm parameters.

Step 2. Initialize the Harmony Memory (HM).

Step 3. Improvise a New Harmony memory.

Step 4. Update the Harmony memory (HM).

Step 5. Repeat Steps 3 and 4 until the termination criterion is satisfied.

5. Neural network structure

The computational models that were enthused by the biological neurons named Artificial Neural Networks (ANN). Neural networks are classically structured in layers. Layers are made up of a number of interconnected nodes. Each node contains an activation function. Patterns

are presented to the network via the input layer, which communicates to one or more hidden layers where the actual processing is done via a system of weighted connections. It has a series of nodes with interconnections where mathematical functions are implemented to do an input/output mapping. The most popular form of neural network structures is the MLP (Multi Layer Perceptron). To achieve correct expression among inputs and outputs, MLP has any number of inputs or outputs with activation function, one or more hidden layers. The actuator function for the entire layer is tanh. Figure 2 shows the structure of neural network. The first layer is input data and the last layer is output layer the rest of them is hidden layer. The ANN which is used in this simulation is a MLP network.

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.

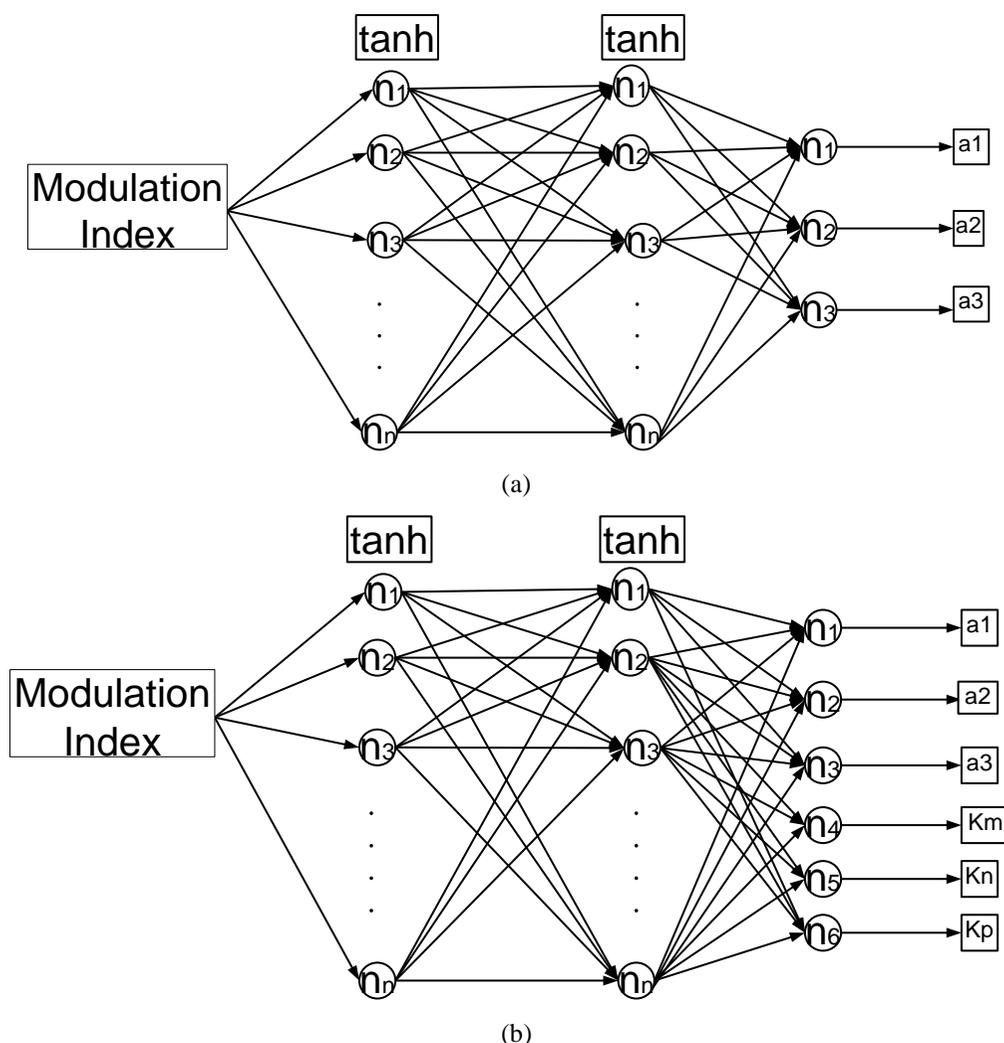


Figure 2. The structure of neural network, a) Constant DC sources, b) Alterable DC sources

The most important 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 employed optimization method might not be guaranteed to converge when far away from a local minimum.

If, the learning algorithm is selected appropriately the resulting ANN can be extremely robust. Due to the importance of the training step, back propagation [25] method has been used in this paper. The optimization method used to determine weight adjustments has a large influence on the performance of neural network. In this study, modulation index is the input of ANNs for both cases with constant and alterable DC links. Figure 2 (a) shows the structure of the ANN for constant DC sources where the switching angles are the output of designed ANNs. For alterable DC sources, switching angles with K_m , K_n and K_p are the output of ANNs, shown in Figure 2 (b).

An important point of an ANN that makes it appropriate for this problem is its flexibility to work with 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 HSA, the ANN has enough flexibility to interpolate and extrapolate the results.

In simple words, the suggested approach can be implemented as following; first, the defined objective functions are minimized using HSA. The obtained optimum solutions versus modulation indexes are gathered in a look up table. These solutions are the switching angles for a case with constant DC sources and are the 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. 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 regard, any values of voltage amplitude with minimum THD can be generated. These voltage amplitudes can be the ones not defined previously in the look up table found by optimization process.

6. Simulation Results

In MTHD convincing V_{l1}^* with obtaining the possible minimum THD_{line} is aimed. The achieved optimum switching angles versus the modulation index for the case with constant DC sources is plotted in Figure 3 (a) and for the case with alterable DC sources is plotted in Figure 3(b). In this figure, α_1 is shown in blue, α_2 is shown in red, and α_3 is shown in green color.

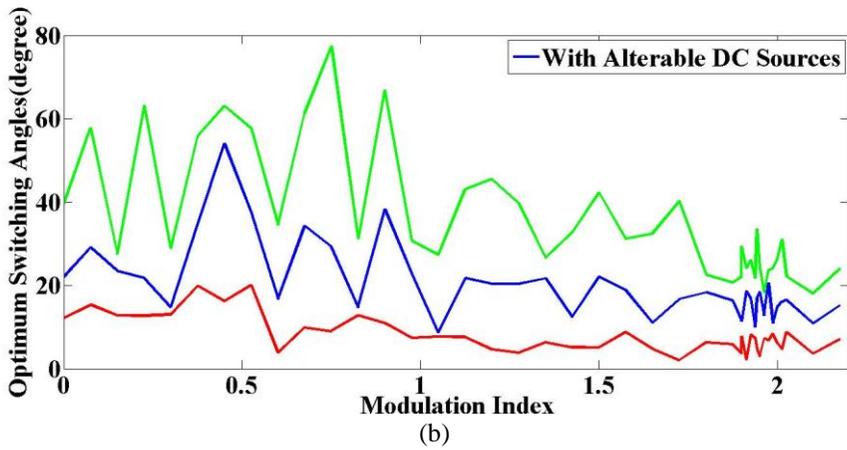
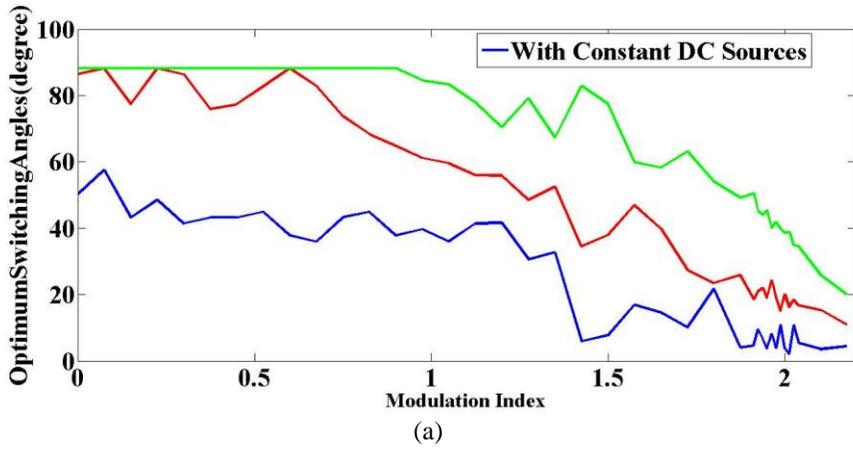
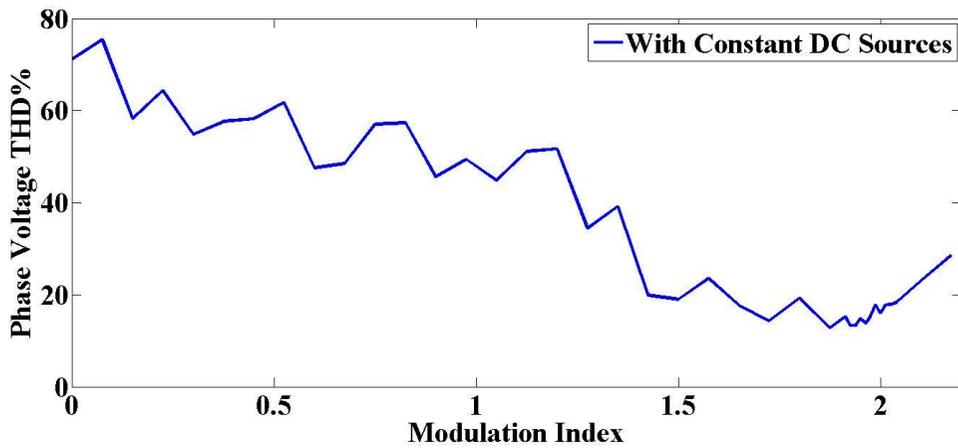
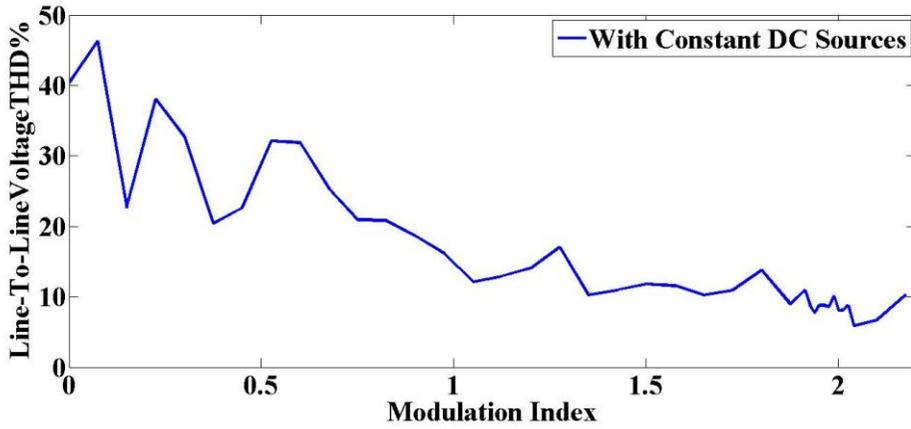
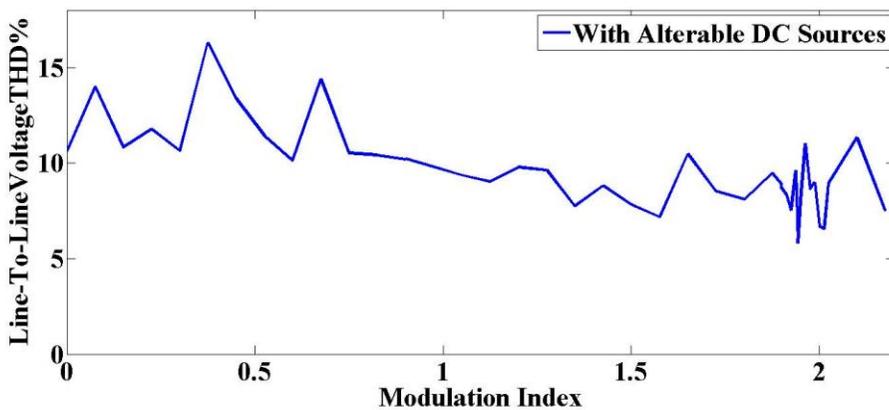
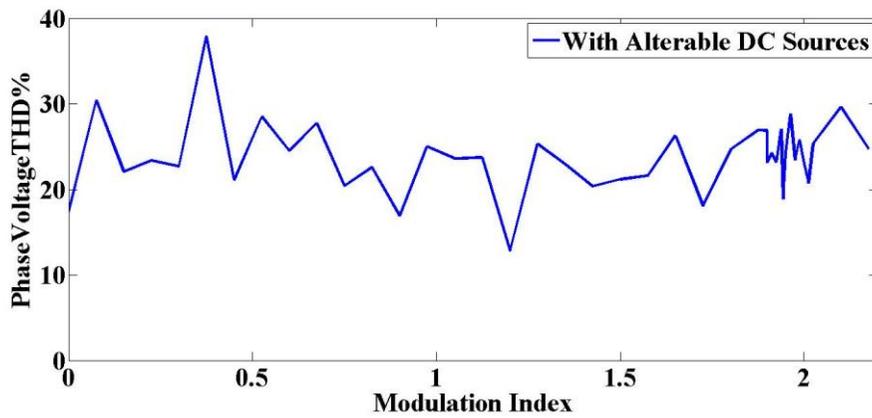


Figure 3. The obtained switching angles per modulation index for the 7-level inverter, a) with constant DC links, b) with alterable DC links





(a)



(b)

Figure 4. THD values versus the modulation index, a) with constant DC links, b) with alterable DC links

As mentioned before, for an application with three phase load, from the load point of view, the line-to-line voltage due to its harmonic spectrum is more essential. The THD values of phase voltage and line-to-line voltage for the case with constant DC links and for the case with alterable DC links are presented in Figure 4(a) and Figure 4(b), respectively. From the variance between line voltage THD and phase voltage THD, it is concluded that there is no definite

respect between phase voltage THD and line to line voltage THD and also there is no necessity to phase voltage result in lower THD value when minimum value of the line-to-line voltage THD is obtained.

Triplet harmonics do not appear in line voltage and it is considered as the main motive of the mentioned Variance. Therefore, if the THD minimization strategy is implemented to line voltage it gives the optimum condition just to the line voltage and this incident is the result of harmonic content of line voltage. In a different explanation, in the line voltage THD minimization procedure, merely the harmonic components existing in the line voltage are considered to gain the optimum condition for the line-to-line voltage. The differences of Line-To-Line voltage THD values between the two mentioned methods can be determined in Figure 5.

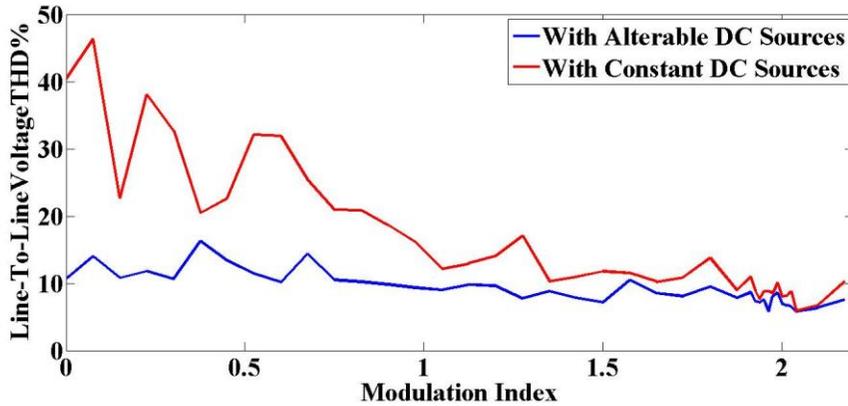
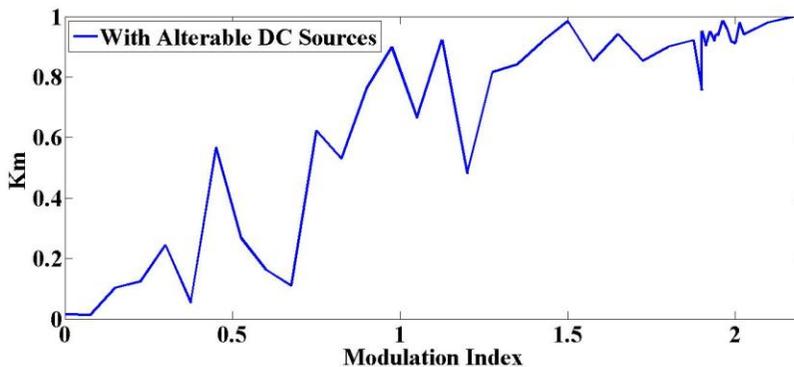


Figure 5. The comparison between Line-to-Line voltage THD values obtained from both methods

As shown in Figure 5, 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. The achieved amplitudes of DC sources are given in Figure 6 for MTHD method for the case with alterable DC links.



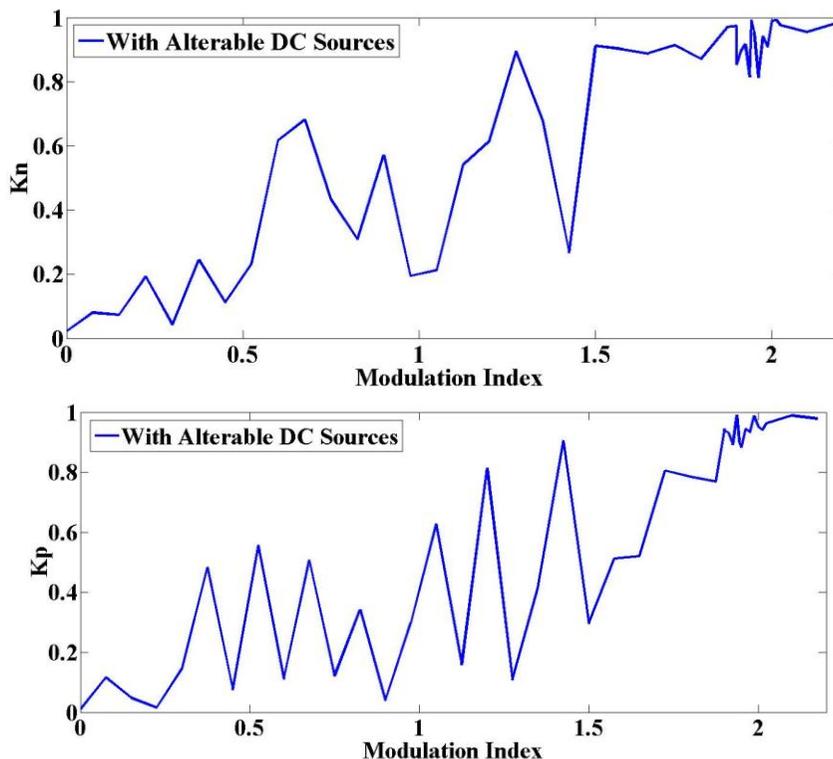


Figure 6. The obtained results for the values of DC sources versus modulation index for the case with alterable DC links

In Table 1 and Table 2, the optimum solutions are given for both cases which the lowest THD of line voltage is caused by them. Table 1 and Table 2 are related to Figure 1 (a) and Figure 1 (b), respectively. The given switching angles are in degrees.

Table I (Figure 1 (a))

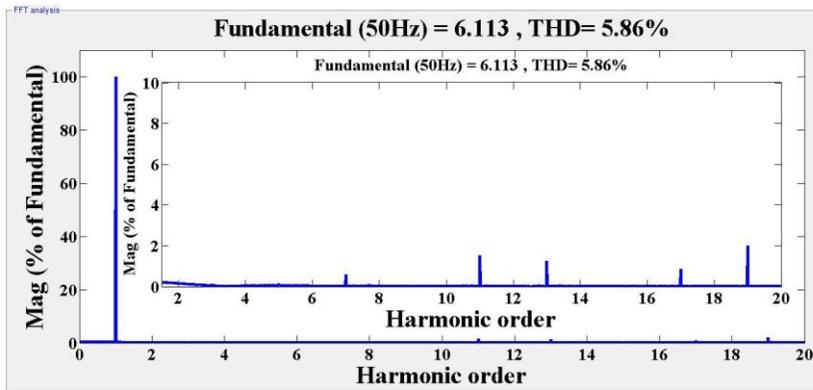
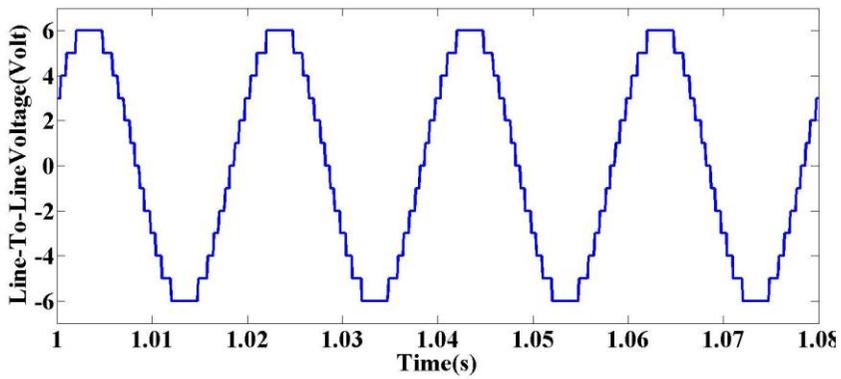
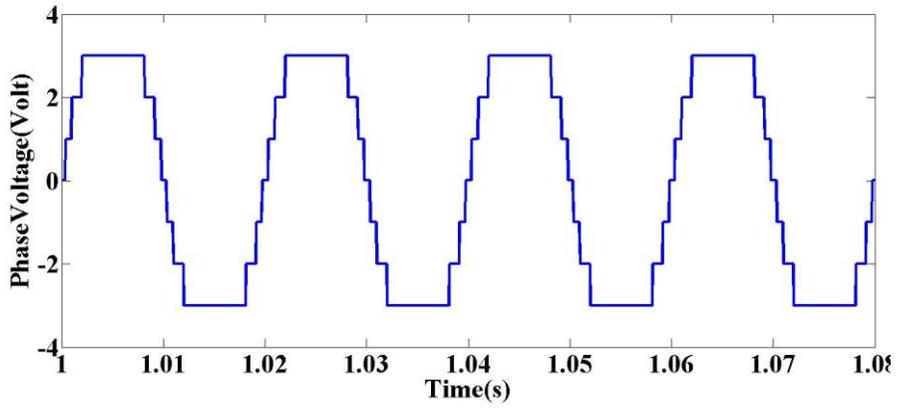
Table 1.

V_1^*	a_1	a_2	a_3	Phase THD%	Line-To-Line THD%
2.04	5.4	16.7	34.4	18.36	5.86

Table 2. (Figure 1 (b))

V_1^*	a_1	a_2	a_3	K_m	K_n	K_p	Phase THD%	Line-To-Line THD%
1.94	4.6238	17.1	33.583	0.9412	0.9931	0.905	18.9	5.82

The tables shown above, infer that the minimum THD value of line voltage gained from using proposed scheme is lower than the THD values given in [17] using GA to solve THD minimization problem, a study similar with this paper. Hence, for MTHD strategy the proposed scheme seems to be more effective than GA. In Figure 7, the related Phase voltage and line-to-line voltage are given for the mentioned V_1^* values, as a case study. Also harmonic content of output line voltage for both cases are represented.



(a)

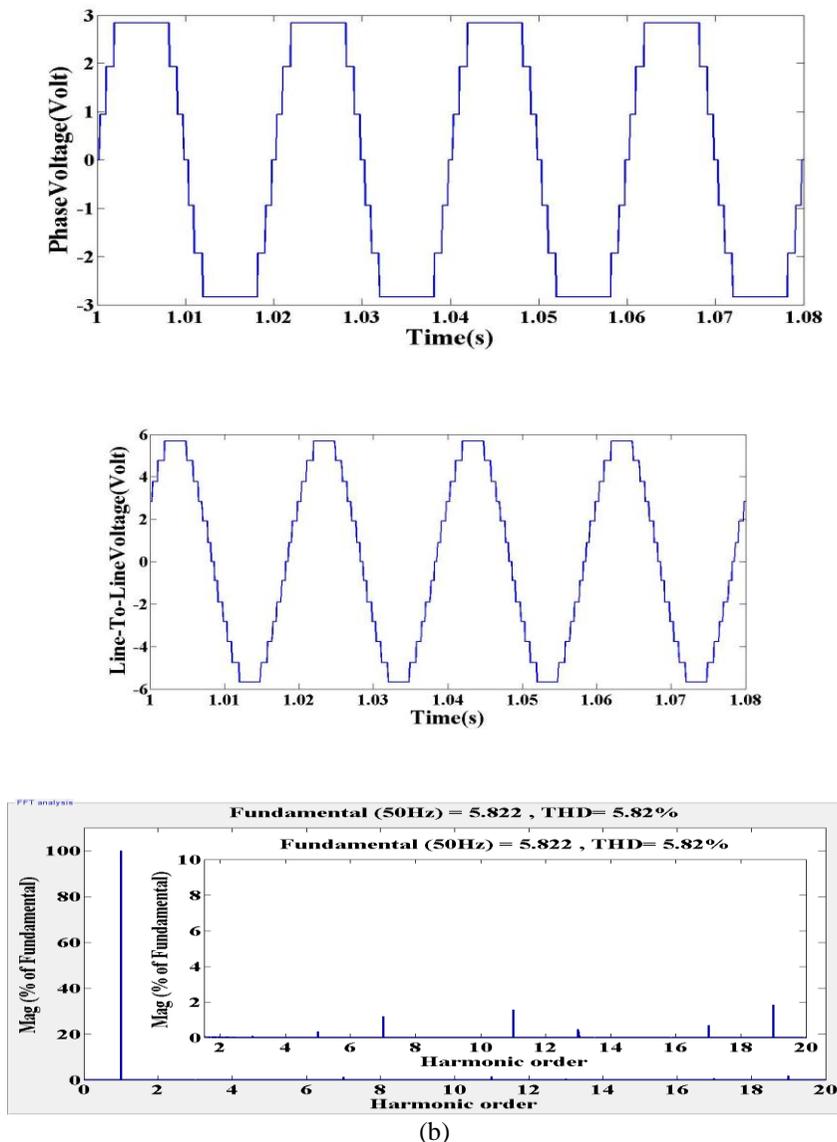


Figure 7 Phase voltage, Line voltage and the harmonic spectra of Line voltage, a) related to Figure 1 (a) and $V_{l1}^* = 2.04$, b) Related to Figure 1 (b) and $V_{l1}^* = 1.94$; where $V_{dc} = 1^v$

It's shown from Figure 7, 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.

7. Experimental Results

The experimental studies are executed to confirm the good performance of the both presented cases. An experimental cascaded based prototype is put in practice. It is noticeable that the types of switches and MOSFET drivers used in the prototype are IRF260 and Hcpl316j, respectively. The DsPIC30F4011 pulse generator has been used to generate all switching patterns. The adjustable DC sources existing in the laboratory have been used to generate the DC voltage links in the configuration.



(a)



(b)



(c)



(d)

Figure 8 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)

Figure 8 shows the obtained results from experimental studies. Figure 8(a)-(b) depict the first case which points to multilevel inverter with constant DC sources and the switching pattern. And Figure 8(c)-(d) show the second case which indicates operation of inverter with alterable DC sources and the switching pattern.

The experimental studies validate the accuracy of results and also feasibility of proposed scheme. It is seen that experimental results cope with the simulation results very nearly.

8. Conclusion

In general the THD minimization is implemented on phase voltage because of its obvious waveform and ease of formulation. The line voltage has got great importance of the load point of view in three phase applications. Hence, minimizing the line voltage THD is very important in three phase applications. This study presents a highly developed strategy of THD minimization. It is implemented straightforward to the line-to-line voltage to reduce the THD value more effectively. 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. Simulation and practical results were presented to show the accuracy of obtained results and the provided comparison with previous works validate the efficiency of the presented method in THD minimization.

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