Harmonic Optimization in Multi-Level Inverters using Harmony Search Algorithm

B. Majidi, H. R. Baghaee, G. B. Gharehpetian (IEEE Senior Member), J. Milimonfared, and M. Mirsalim, (IEEE Senior Member)

[*] Center of Excellence in Power Engineering, Amirkabir University of Technology, Tehran, Iran
[+] Also, with the Department of Engineering, St. Mary's University, San Antonio, TX, USA.
e-mails: bmx@aut.ac.ir, hrbaghaee@aut.ac.ir, grptian@aut.ac.ir, monfared@aut.ac.ir and mmirsalim@aut.ac.ir

***Abstract*—This paper presents a new method to optimize harmonic stepped waveform for multi-level inverters using harmony search algorithm. The method has the benefit of high rate of convergence and precision compared to other conventional optimization methods. The proposed technique can be applied to multi-level inverters with any number of levels. The goal of optimization is to eliminate some low order harmonics and to maintain the fundamental component at the desired value. As a case study, the method is applied and tested on a 13-level inverter. Simulation results show the effectiveness and flexibility of the proposed method.**

***Keywords* — Multi-Level Inverter, Harmonics, Harmony Search Algorithm, Genetic Algorithm.**

INTRODUCTION

Nowadays, dc-to-ac inverters are widely used in industry. All applications are mainly divided into two general groups: 1- Electric drives for all ac motors when dc supply is used and 2- in systems including high voltage direct current (HVDC) transmission systems, custom power & flexible ac transmission systems (FACTS) devices, flexible distributed generation (FDG) and interconnection of distributed generation (DG) units to a grid. Several switching algorithm such as pulse width modulation (PWM), Sinusoidal Pulse Width Modulation (SPWM), space-vector modulation (SVM), selective harmonic eliminated pulse width modulation (SHEPWM) or programmed-waveform pulse width modulation (PWPWM) are applied extensively to control and determine switching angles to achieve the desired output voltage. In the recent decade, a new kind of inverter named multi-level inverter, has been introduced. In various publications, this inverter has been used in place of the common inverters to indicate its advantages in different applications. Being multi-level, it can be used in high power and high voltage applications. In order to reach the desired fundamental component of voltage, all of various switching methods produce harmonics and hence, it is of interest to select the best method to achieve minimum harmonics and total harmonic distortion (THD). It is suggested to use optimized harmonic stepped waveform (OHSW) to eliminate low order harmonics by determining proper angles and then removing the rest of the harmonics via filters. In addition, this technique lowers switching frequency down to the fundamental frequency and consequently, power losses and cost are reduced.

Traditionally, there are two states for DC sources in multi-level inverter: 1- Equal DC sources 2- Non equal DC sources. Several algorithms have been suggested for the above purposes. In [1] Newton-Raphson method has been discussed to solve equations. Newton-Raphson method is fast and exact for those modulation indices (M) which can satisfy equations; but it cannot obtain the best answer for other indices. Also, [2] has used the mathematical theory of resultants to find the switching angles such that all corresponding low order harmonics are completely canceled out sequentially for both equal and non-equal DC sources separately. However, by increasing levels of multi-level converters, equation set tends to a high order polynomial which narrows its feasible solution space. In addition, this method cannot suggest any answer to minimize harmonics of some particular modulation indices where there is no acceptable solution for the equation set. Genetic algorithm (GA) method has been presented in [3] to solve the same problem with any number of levels for both eliminating and minimizing the harmonics, but it is not fast and exact enough. This method has also been used in [4] to eliminate mentioned harmonics for non-equal DC sources. Moreover, all optimal solutions have used main equations in fitness function. This means that the fundamental component cannot be satisfied exactly.

In this paper, a harmony search (HS) algorithm approach will be presented. The problem can be solved with a simpler formulation and with any number of levels without extensive derivation of analytical expressions. It is also faster and more precise than GA.

I. CASCADE H-BRIDGES

The cascaded multi-level inverter is one of the several multi-level configurations. It is formed by connecting several single-phase, H-bridge converters in series as shown in Fig. 1.a for a 13-level inverter. Each converter generates a square-wave voltage waveform with different duty ratios. Together, these form the output voltage waveform, as shown in Fig. 1.b. A three-phase configuration can be obtained by connecting three of these converters in Y or Δ. For harmonic optimization, the switching angles θ_1, θ_2,…and θ_6 (for a 13-level inverter) shown in Fig. 1.b have to be selected so that certain order harmonics are eliminated.

II. Problem Statement

Fig. 1.b shows a 13-level inverter. θ_1, θ_2,…and θ_6 are variables and should be determined. Each full-bridge inverter produces a three level waveform $+V_{dc}$, $-V_{dc}$ and 0, and each angle θ_i is related to i^{th} inverter $i = 1,2,...,S$. S is the number of DC sources that is equal to the number of switching angles (in this study S=6). The number of levels, L, is calculated as $L = 2S + 1$. Considering equal amplitude of all dc sources, the Fourier series expansion of the output voltage waveform is as follows:

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

where V_n is the amplitude of harmonics. The angles are limited between zero and 90 ($0 < \theta_i < \pi/2$). Because of odd quarter-wave symmetric characteristic, the harmonics with even order become zero. Consequently, V_n will be as follows:

$$V_n = \begin{cases} \dfrac{4V_{dc}}{n\pi} \sum_{i=1}^{k} \cos(n\theta_i) & for\ odd\ n \\ 0 & for\ even\ n \end{cases} \quad (2)$$

There are two approaches to adjust the switching angles:

1. Minimizing the THD that is not common because some low order harmonics may remain.

2. Canceling the lower order harmonics and removing the remained harmonics with a filter.

The second approach is preferred. For motor drive applications, it is necessary to eliminate low order harmonics, from 5 to 17. Hence, in this paper, a 13-level inverter is chosen to eliminate low harmonics from 5 to 17. It is not needed to delete triple harmonics because they will be eliminated in three phase output. Thus, for a 13-level inverter, Eq. (2) results in (3).

$$\begin{aligned} M &= \cos(\theta_1) + \cos(\theta_2) + ... + \cos(\theta_6) \\ 0 &= \cos(5\theta_1) + \cos(5\theta_2) + ... + \cos(5\theta_6) \\ &\vdots \\ 0 &= \cos(17\theta_1) + \cos(17\theta_2) + ... + \cos(17\theta_6) \end{aligned} \quad (3)$$

where, M is the modulation index and defined as:

$$M \triangleq \frac{V_1}{4V_{dc}/\pi} \quad (0 < M \le 6) \quad (4)$$

It is necessary to determine six switching angles, namely θ_1, θ_2,…and θ_6 so that equation set (3) is satisfied. These equations are nonlinear and different solution methods can be applied to them.

III. Genetic Algorithm

In order to optimize the THD, genetic algorithm (GA) which is based on natural evolution and population is implemented. This algorithm is usually used to reach a near global optimum solution. In each iteration of GA (referred as generation), a new set of string (.i.e. chromosomes) with improved fitness is produced using genetic operators (i.e. selection, crossover and mutation).

A. Chromosome's structure

Chromosome structure of a GA is shown in Fig. 2. This involves the θ_i as parameter of the inverter.

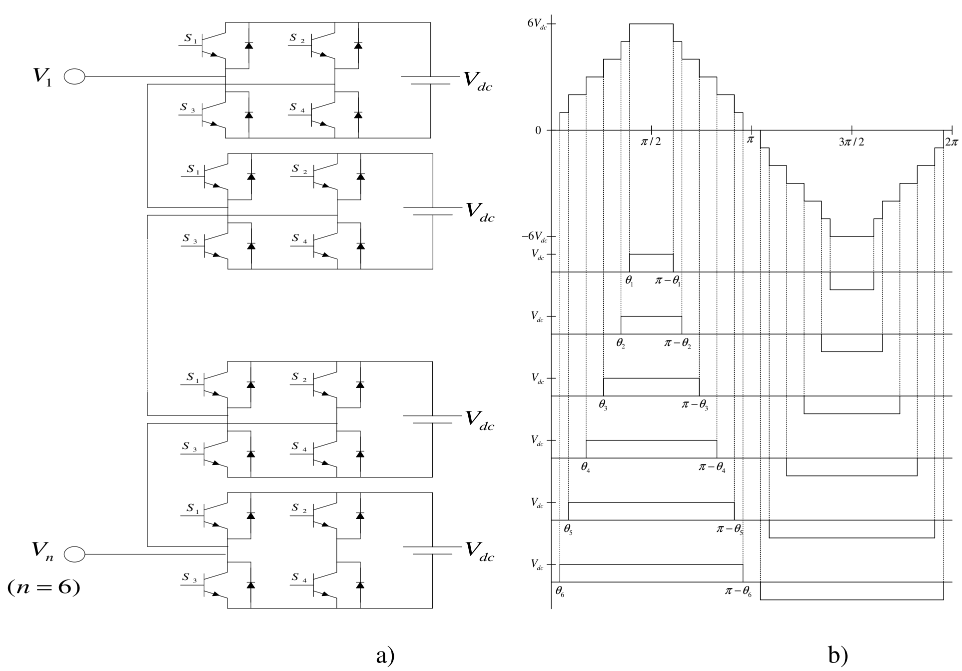


Fig. 1: a) Multi-Level Inverter b) Multi-Level waveform generation

B. Selection

The method of tournament selection is used for selections in a GA [5-6]. This method chooses each parent by choosing

4.75	13.02	30.26	43.55	87.36	89.82

Fig 2: A typical chromosome

n_t (tournament size) players randomly, and choosing the best individual out of that set to be a parent. In this paper n_t is chosen as 4.

C. Cross Over

Cross over allows the genes from different parents to be combined in children by exchanging materials between two parents. Cross over function randomly selects a gene at the same coordinate from one of the two parents and assign it to the child. For each chromosome, a random number is selected. If this number is between 0.01 and 0.3 [6], the two parents are combined; else chromosome is transferred with no cross over.

D. Mutation

GA creates mutation children by randomly changing the genes of individual parents. In this paper, GA adds a random vector from a Gaussian distribution to the parents. For each chromosome, random number is selected. If this number is between 0.01 and 0.1 [6], mutation process is applied; else chromosome is transferred with no mutation.

IV. Harmony Search Algorithm

Harmony Search (HSA) Algorithm has recently been developed in an analogy with music improvisation process where music players improvise the pitches of their instruments to obtain better harmony [7]. The steps in the procedure of harmony search are shown as follows [8]:

Step 1: Initialize the problem and algorithm parameters.
Step 2: Initialize the harmony memory.
Step 3: Improvise a new harmony.
Step 4: Update the harmony memory.
Step 5: Check the stopping criterion.
These steps are described in the next five subsections.

A. Initialize the problem and algorithm parameters

In Step 1, the optimization problem is specified as follows:

$\min\{f(x) \mid x \in X\}$ subject to $g(x) \geq 0$ and $h(x) = 0$

where *f(x)* is the objective function and *g(x)* is the inequality constraint function; *h(x)* is the equality constraint function. *x* is the set of each decision variable, x_i, and *X* is the set of the possible range of values for each decision variable, that is $X_{i,\min} \leq X_i \leq X_{i,\max}$, where $X_{i,\min}$ and $X_{i,\max}$ are the lower and upper bounds of each decision variable. The HS algorithm parameters are also specified in this step. These are the harmony memory size (HMS), or the number of solution vectors in the harmony memory, harmony memory considering rate (HMCR), pitch adjusting rate (PAR), the number of decision variables (N) and the number of improvisations (NI), or stopping criterion. The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. This HM is similar to the genetic pool in the GA [9]. Here, HMCR and PAR are parameters which are used to improve the solution vector. Both of them will be defined in Step 3.

B. Initialize the harmony memory

In Step 2, the HM matrix is filled with as many randomly generated solution vectors as the HMS

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \quad (5)$$

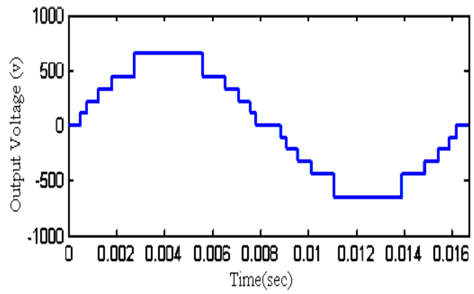
C. Improvise a new harmony

A new harmony vector, $x_i' = (x_1', x_2', \ldots, x_N')$, is generated based on three rules: (1) memory consideration, (2) pitch adjustment and (3) random selection. Generating a new harmony is called 'improvisation' [9]. In the memory consideration, the value of the first decision variable x_1' for the new vector is chosen from any value in the specified HM range $(x_1^1 - x_1^{HMS})$. Values of the other decision variables, $(x_2', x_3', \ldots, x_N')$, are chosen in the same manner. The HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while (1-HMCR) is the rate of randomly selecting one value from the possible range of values.

$$x_i' \leftarrow \begin{cases} x_i' \in \{x_i^1, x_i^2, \ldots, x_i^{HMS}\} & \text{with probability } HMCR \\ x_i' \in X_i & \text{with probability } (1-HMCR) \end{cases} \quad (6)$$

For example, a HMCR of 0.85 indicates that the HS algorithm will choose the decision variable value from historically stored values in the HM with 85% probability or from the entire possible range with 100–85% probability. Every component obtained by the memory consideration is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:

$$x_i' \leftarrow \begin{cases} Yes & \text{with probability } PAR \\ No & \text{with probability } (1-PAR) \end{cases} \quad (7)$$



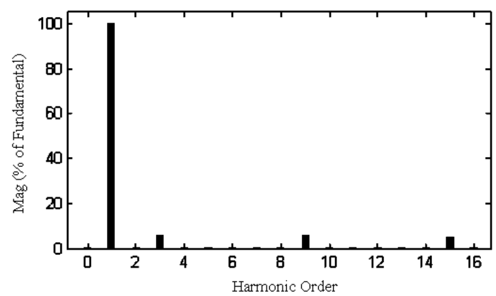


Fig.3: a) output voltage waveform b) harmonic spectrum

The value of (1-PAR) sets the rate of doing nothing. If the pitch adjustment decision for x_i' is Yes, x_i' will be replaced as follows:

$$x_i' \leftarrow x_i' \pm rand()*b_w$$

where b_w is an arbitrary distance bandwidth and rand () is a random number between 0 and 1.

In Step 3, HM consideration, pitch adjustment or random selection is applied to each variable of the new harmony vector in turn.

D. Update harmony memory

If the new harmony vector, $x_i' = (x_1', x_2', ..., x_N')$ is better than the worst harmony in the HM, judged in terms of the objective function value, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

E. Check stopping criterion

If the stopping criterion (maximum number of improvisations) is satisfied, the computation will be terminated. Otherwise, Steps 3 and 4 are repeated.

V. SIMULATION RESULTS

Harmony Search algorithm has been used to solve the optimization problem. The objective function has been chosen as follows:

$$f = \left\{ \left(100 \frac{V_1^* - V_1}{V_1^*}\right)^4 + \sum_{i=2}^{6} \frac{1}{h}\left(50 \frac{V_i}{V_1}\right) \right\} \quad (8)$$

where V_1^* is the desired fundamental harmonic, $h_1=1$, $h_2=5$ … and $h_6=17$, are orders of the first six viable harmonics at the output of a three phase multi-level inverter, respectively. The parameters of the harmony search algorithm have been chosen as: *HMS*=10, *HMCR*=0.9, *PAR*=0.6 and b_w =0.01. The optimal solution vector is obtained after 1000 iterations as: [10.757, 16.35, 26.973, 39.068, 59.409, 59.409]. With these switching angles, the output voltage waveform and its spectrum will be obtained as shown in Fig. 3. The values of the objective function and the total harmonic distortion (THD) has been obtained as: $THD = 4.73\%$ and $f = 4.8e-8$. Simulation has been also performed by GA and results obtained as: $THD = 7.11\%$ and $f = 0.05$. It is obvious that the harmony search algorithm performed much better than GA approach.

VI. CONCLUSION

In this paper, the harmony search algorithm was proposed for harmonic optimization in multi-level inverters. Harmony search algorithm has more flexibility over conventional methods. This method can obtain optimum switching angles for a wide range of modulation indices. This advantage is of importance, especially when the number of switching angles goes up, where equation set may not have any solution, or when it is solvable only for a short range of modulation indices. Moreover, the implementation of the harmony search algorithm is very straightforward compared to the conventional methods like Newton-Raphson, where it is necessary to calculate the Jacobean matrix. In addition, one of the most attractive features of intelligent algorithms is their independency from case studies. Actually, intelligent algorithm can be imposed to a variety of different problems without any need for extensive manipulations. For example, the harmony search algorithm and GA algorithms are able to find optimum switching angles in order to cancel out low order harmonics, and if it is not possible to completely remove them, they can suggest optimum switching angles so that low order harmonics will be reduced as much as possible. Furthermore, with a little manipulation in the defined objective function, one can use HSA and GA as a tool for THD optimization. Also, the results indicate that, harmony search algorithm has many benefits over GA such as simplicity in the implementation, precision and speed in global convergence.

REFERENCES

[1] Jason Lai, Chair Dusan Borojevic Alex Q. Huang, "Optimized harmonic Stepped Waveform fro Multi-Level Inverters", M.s.c thesis, Virginia Polytechnic Institute and State University, 1999.

[2] J. Chiasson, L. Tolbert, Keith McKenzie and Zhong Du; "Eliminating Harmonics in a Multi-level Converter using Resultant Theory", IEEE Transactions on Control Systems Technology, 2005, Vol. 13, pp. 216 - 223.

[3] B. Ozpineci, L. M. Tolbert and J. N. Chiasson, "Harmonic optimization of multi-level converters using genetic algorithms," Proceeding on 35th IEEE Power Electronics Specialists Conference, 2005, Vol. 5, pp. 3911 – 3916.

[4] M. G. Hosseini Aghdam, S. H.Fathi and A. Ghasemi, "Modeling and Simulation of Three-Phase OHSW Multi-level Voltage-Source Inverter by Means of Switching Functions", IEEE International Conference on Power Electronics and Drives Systems, 2005. Vol. 1, pp. 633- 641.

[5] B. L. Miller and D. E. Goldberg, “Genetic Algorithms, Tournament Selection, and the Effects of Noise,” Complex Systems, pp. 193-212, June 1995.
[6] MATLAB Genetic Algorithm and Direct Search Toolbox User’s Guide, The Math Works, 1998.
[7] ZW. Geem, C. Tseng and Y. Park, 'Harmony search for generalized orienteering problem: best touring in China", Springer Lecture Notes for Computer Science, 2005, Vol. 341, pp.741–50.
[8] ZW. Geem, JH. Kim and GV. Loganathan, "Harmony search optimization: application to pipe network design", International Journal of Modelling and Simulation, 2002, Vol, 22, pp.125–33.
[9] KS. Lee and ZW. Geem, "A new structural optimization method based on the harmony search algorithm", Computer Structure, 2004, Vol. 82, pp. 781–98.
[10] M. Young, *The Technical Writer's Handbook*. Mill Valley, CA: University Science, 1989.