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Elimination of Low Order Harmonics in Multilevel Inverter Using Nature-Inspired Metaheuristic Algorithm

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***Abstract*—**Nature-inspired metaheuristic algorithms, particularly those founded on swarm intelligence, have attracted much attention over the past decade. Firefly algorithm has appeared in approximately seven years ago, its literature has enlarged considerably with different applications. It is inspired by the behavior of fireflies. The aim of this paper is the application of firefly algorithm for solving a nonlinear algebraic system. This resolution is needed to study the Selective Harmonic Eliminated Pulse Width Modulation strategy (SHEPWM) to eliminate the low order harmonics; results have been applied on multilevel inverters. The final results from simulations indicate the elimination of the low order harmonics as desired. Finally, experimental results are presented to confirm the simulation results and validate the efficaciousness of the proposed approach.

***Keywords*—**Firefly algorithm, metaheuristic algorithm, multilelvel inverter, SHEPWM.

I. Introduction

METAHEURISTICS methods inspired by nature are currently among the most powerful tools for the optimization of many non-linear hard combinatorial problems (NP-hard). These methods are based on an existing biological mechanisms natural phenomenon. Natural systems are those of the most interesting inspiration to design new techniques dedicated to solve many optimization problems. Particle Swarm Optimization (PSO), a colony of ants and bee colony algorithms are methods inspired by the observation of nature. These optimization algorithms use the behavior of the swarm intelligence. They are based on live insects or simple interactions between individual entities [1], [2]. This is the subject of this work.

The firefly algorithm (FA), proposed by Xin-She Yang at the University of Cambridge, is a new metaheuristic algorithm, which is inspired by the behavior of fireflies. Their population is estimated at about two thousand species of fireflies. Most of them produce short, rhythmic flashes. Their flashing light, generated by a process of bioluminescence, can be used as part of courtship rituals or signals [1]-[3].

Multilevel inverters are controlled by PWM strategies. Among the most well known strategies, one finds SHEPWM [4]-[6] which is the subject of this work. This strategy consists in calculating the switching angles (firing angles) for the multilevels inverter to have a shape nearest sinusoidal. But to find the switching angles, we must solve an algebraic nonlinear equations. In this paper, we will solve this system by the application of FA.

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II. FA

In the FA, the objective function (or fitness) of a given optimization problem is based on the differences in light intensity. It helps fireflies to move towards brighter and more attractive places for optimal solutions. All fireflies are characterized by their light intensity associated with the objective function. Each firefly is changing its position iteratively. The FA has three rules [1]-[3]:

- All fireflies are unisex, and they will move towards more attractive and brighter ones.
- The attractiveness of a firefly is proportional to its brightness that decreases as the distance from the other firefly increases. If there is not a more attractive firefly than a particular one, it will move randomly.
- The brightness of a firefly is determined by the value of the objective function. For maximization problems, the brightness is proportional to the value of the objective function.

Each firefly has its attractiveness β described by monotonically decreasing function of the distance between two any fireflies:

$$\beta(r) = \beta_0 e^{-\gamma r^m}, \qquad m \geq 1 \tag{1}$$

where β_0 designates the maximum attractiveness (at r = 0) and γ is the light absorption coefficient, which controls the decrease of the light intensity.

The distance between two fireflies i and j at positions x_i and x_j can be defined as [1], [3]:

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{2}$$

where $x_{i,k}$ is the *k-th* component of the spatial coordinate x_i of i-th firefly and d represents the number of dimensions.

The movement of a firefly *i* is described by the following form [1]:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha(rand - \frac{1}{2}) \quad (3)$$

where the current position of a firefly i is represented by the first term, the second term represents a firefly's attractiveness and the third term is used for the random movement if there is no any brighter firefly (rand is a random number generator uniformly distributed in the range < 0, 1 >). For most cases β_0=1, α ∈ [0, 1]. In practice, the light absorption coefficient γ varies from 0.1 to 10. This parameter describes the variation of the attractiveness and its value is responsible for the speed of FA convergence [1]. The pseudo-code of the FA can appear as in Fig. 1 [1], [2].

```
1. Initialize algorithm's parameters:
      – number of fireflies (n),
      – β0, γ , α,
      – maximum number of generations (iterations, MaxGen).
   Define the objective function f (x),  x = (x1, . . . , xd)^T.
   Generate initial population of fireflies  xi (i = 1, 2, . . . , n)
   //generate n initial solutions
   Light intensity of firefly Ii at xi is determined by value of objective function f (xi )
2. While k < MaxGen//(k = 1 : MaxGen)
   For i = 1:n  //all n fireflies
     For j = 1:n
        If (Ij> Ii) move firefly i towards firefly j in d-imension according to Eq. (3);  End if
        Obtain attractiveness, which varies with distance r according to Eq. (1)
        Find new solutions and update light intensity
     End for j
   End for i
     Rank the fireflies and find the current best
   End while
3. Find the firefly with the highest light intensity,  visualization
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Fig. 1 Pseudo-code of the FA

The initial population of fireflies is generated in the following form:

$$x_i = LB + rand \cdot (UB - LB) \quad (4)$$

where LB and UB represent the lower and the upper bounds of *i-th* firefly.

After the evaluation of the initial population the FA enters its main loop, which represents the maximum number of generations of the fireflies (iterations). For each generation, the firefly with the maximum light intensity (the solution with the best value of objective function) is chosen as the potential optimal solution. The FA simulates a parallel run strategy. The population of n fireflies generates n solutions.

The application of FA can solve many optimization problems [1]-[3]. One of theme is the SHEPWM non linear equations.

III. SHEPWM for Multilevel Inverter

It is a strategy based on the generation of a succession of variable widths pulses wave to establish the wave of the output voltage of the inverter [7]. Generally, in the case of a single phase or three-phase multilevel inverter, there are:

– A double symmetry in voltage Va, Vb and Vc compared to π/2 and π. Then, the even harmonics are null.
– A balanced three-phase system voltage, then the amplitudes of the triplen harmonics are null too.

This wave is characterized by the number of pulses or impulses by alternation. ***C*** represents the number of switching angles per quarter of period. Whatever the ***C is*** odd or even, ***C*** angles are enough to determine the width of the whole of the impulses. These switching angles are given in such way to eliminate definite harmonics. In this study, we were interested to eliminate the first harmonic (5, 7, 11, 13...) in the case of three-phase inverters, which are the most troublesome for voltage and therefore embarrassing for the ideal operation loads such as electric motors [4].

Fig. 2 illustrates an example of a generalized curve on first quarter of period of the voltage V_{AM} delivered by the five level three-phase inverter.

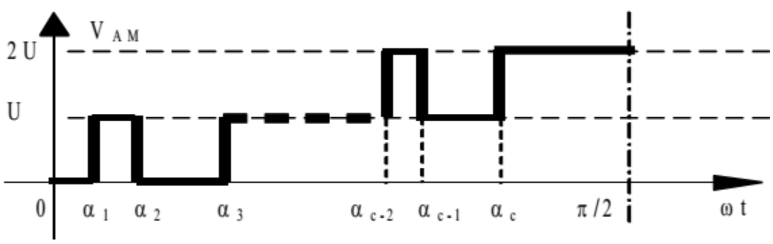

Fig. 2 Form of the first quarter of the voltage VAM

According to the characteristic of the wave (symmetry with respect to the half and the quarter of the period), the Fourier series will be simplified and the study will be limited only to the first quarter of the period of this wave.

The decomposition in Fourier series, which only show the existence of harmonics of odd natures [4], [5], [7], [10], [11], is given by:

$$V_{AM}(\omega t) = \sum_{n=1}^{\infty} b_n \sin(n\omega t) \quad (5)$$

where

$$\begin{cases} b_n = \dfrac{4}{\pi}\displaystyle\int_0^{\frac{\pi}{2}} V_{AM}(\omega t)\cdot\sin(n\omega t)\,d\omega t & n \quad odd \\ b_n = 0 & n \quad oven \\ a_n = 0 & \forall n \end{cases} \quad (6)$$

After integration, there will be the equation

$$h_n = \frac{4U}{n\pi}\left[S_1\cos(n\alpha_1)+S_2\cos(n\alpha_2)+..+S_c\cos(n\alpha_c)\right] \quad (7)$$

for n harmonic, nonlinear equations system (set of nonlinear transcendental equations) admitting several solutions.

$$\begin{cases} h_1 = \dfrac{4U}{\pi}\left[S_1\cos(\alpha_1)+S_2\cos(\alpha_2)+\cdots+S_c\cos(\alpha_c)\right] \\ h_3 = \dfrac{4U}{3\pi}\left[S_1\cos(3\alpha_1)+S_2\cos(3\alpha_2)+\cdots+S_c\cos(3\alpha_c)\right] \\ \quad\ddots \\ h_n = \dfrac{4U}{n\pi}\left[S_1\cos(n\alpha_1)+S_2\cos(n\alpha_2)+\cdots+S_c\cos(n\alpha_c)\right] \end{cases} \quad (8)$$

n: an odd number no-multiple of three. U : supply voltage. h_i: harmonic components (i^{th} harmonic order) of the output voltage V_A. h_1: fundamental of the output voltage V_A. α_i: switching angles. S_i: the sign of (cos) equal to +1 or -1. For C unknowns, C-1 harmonics can be eliminated. C angles and C equations are necessary. The solution must respect the following condition (9):

$$0<\alpha_1<\alpha_2<\cdots<\alpha_{C-1}<\alpha_C<\frac{\pi}{2} \quad (9)$$

The system (8) must be solved by a numerical method [5] such as Newton-Raphson [4], [6], [10] or Metaheuristic algorithm [6], [8], [9], [11]. In this work, the FA will be used to solve this system.

IV. Results and Discussion

As mentioned, the system equations are nonlinear. In order to solve this system equations the FA, which is based on natural evolution and populations, is implemented. This algorithm is usually used to reach a near global solution. In each iteration of the FA, a new set of strings, which are called Firefly, with improved fitness produced using the pseudo-code of the FA.

To find the system equations that represent the different shape of V_{AM} tension, it is necessary:

- to replace in the system (8) the values of S_i by +1 for the angle where there is a jump of lower level to the upper level and -1 for the contrary case [4].
- In the case of three-phase inverters, the numbers ***n*** are odd and no-multiple of three.
- The number of ***d*** dimension is the number of the angle ***C*** (d=C).
- The values of $x_{i,k}$ are the angles α_i
- Light intensity of firefly I_i is the objective function (I_i = Fitness).

To define the objective function (or fitness) for FA, it is necessary to know that this algorithm makes the search of maximum of the objective function and in the case of SHPWM, it serves to find the solution that gives the fitness equal to zero. For that reason, the objective function is defined as:

$$Fitness = -\left(|h_1 - r|^4 + |h_3|^2 + |h_5|^2 + \cdots + |h_n|^2\right) \quad (10)$$

with $r = \dfrac{h_1}{2U}$.

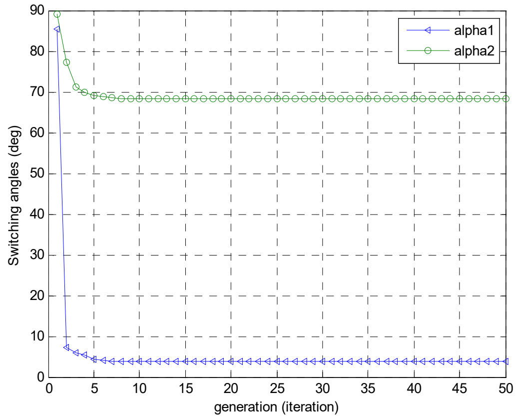

Fig. 3 Behavior of the best solutions (α1 α2) in the population of fireflies to eliminate the 5th harmonic (r = .8)

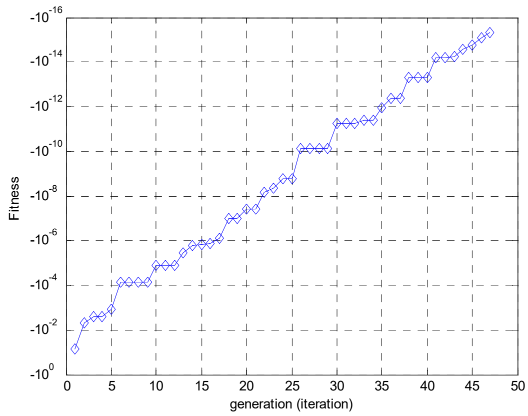

Fig. 4 Fintess of the best solutions (α1 α2) versus generation (iteration)

In the case of a three level three-phase inverter, Fig. 3 shows the behavior of the best solutions (α_1 α_2) in the population of fireflies to eliminate the 5th order harmonic for r

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= 0,8. The fitness of the best solutions is shown in Fig. 4. In this case, the final solutions, in degree, are α1 = 3.689848200642502° and α2 = 68.308028335496740°.

The results of programming giving the various switching angles and different value of C according to the modulation index r are given on:

– Figs. 5 and 6 for three-level inverter;
– Fig. 7 for five-level inverter;
– Fig. 8 for seven-level inverter.

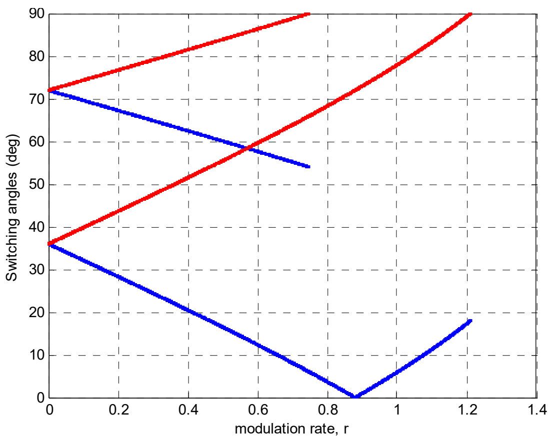
A. Three-Phase Three Level Inverter

In this part, it is desired to eliminate harmonics for three-phase inverter (h_5), (h_5, h_7) and (h_5, h_7, h_{11}).

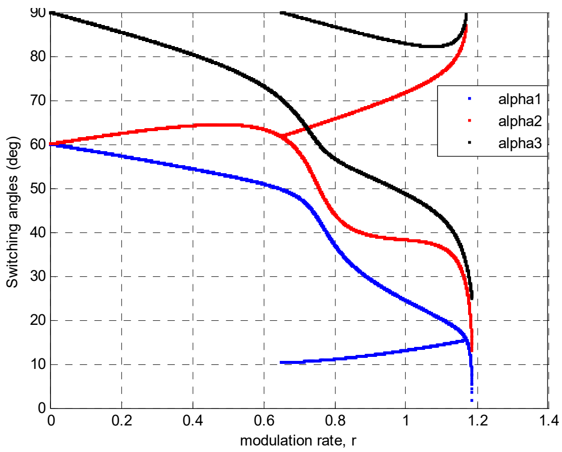
The inverter output supplies a signal of three level of voltage (Uc, 0, Uc), which can be represented by various forms depending on the number of harmonics to be eliminated. In fact, to eliminate only the fifth harmonic, it is necessary to determine two switching angles (α_1 and α_2).

B. Three-Phase Five Level Inverter

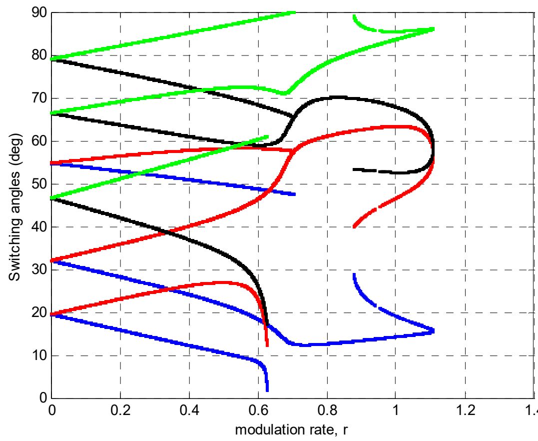
Now, it's chosen to eliminate one, two and three harmonics (h_5), (h_5, h_7) and (h_5, h_7, h_{11}).



(a) Two switching angles to eliminate h5 for three level inverter Si = [1, -1]

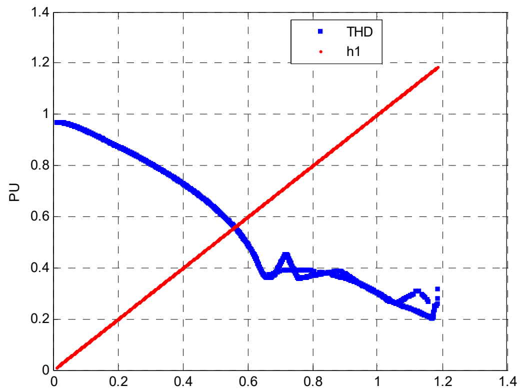


(b) Three Switching angles to eliminate h5 and h7. Si = [1, -1, 1]

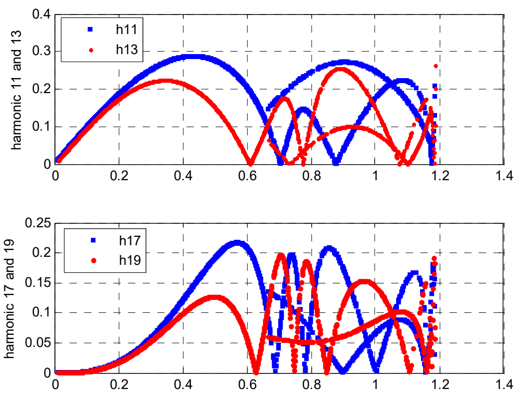


(c) Four Switching angles to eliminate harmonics h5, h7 and h11. Si = [1, -1, 1, -1]

Fig. 5 Switching angles for three level inverter versus modulation index: (a) two angles (b) three angles (c) four angles



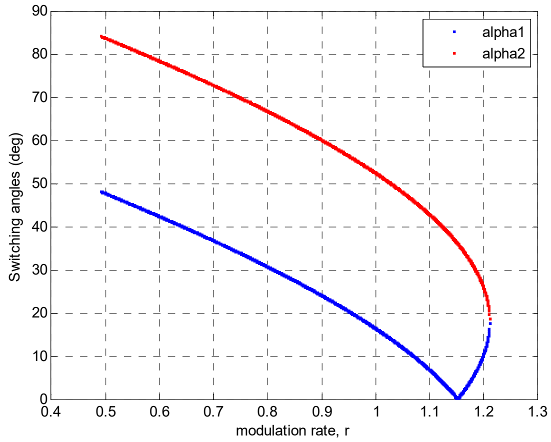
(a) Voltage THD and h1



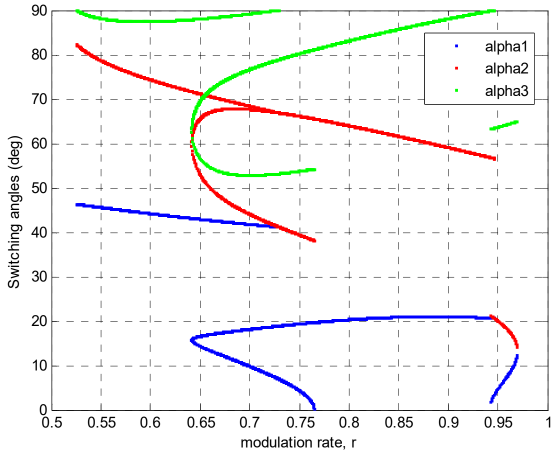
(b) Amplitude of the firsts no eliminated harmonics

Fig. 6 Characteristics of the line voltage VAversus modulation index for 3-level inverter (C = 3, values in (PU))

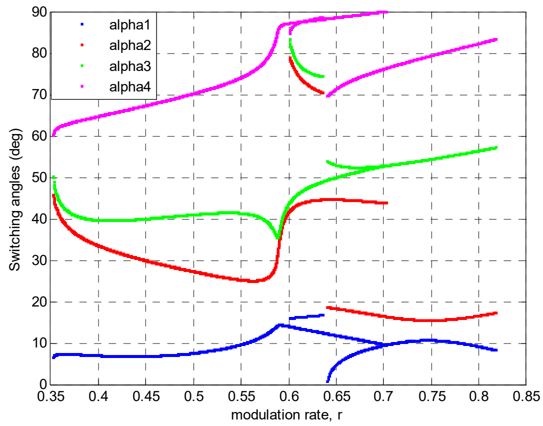
The inverter delivers five-level of voltage (2Uc, Uc, 0, - Uc, -2Uc). To have the two positive levels with the zero on the first quarter of period, the minimum necessary number of angle is two angles of commutation. These angles will permit to eliminate only one harmonic (h_5).



(a) Two switching angles to eliminate h_5 for five level inverter Si = [1, 1]



(b) Three switching angles to eliminate h_5 and h_7. S_i = [1, 1, -1]



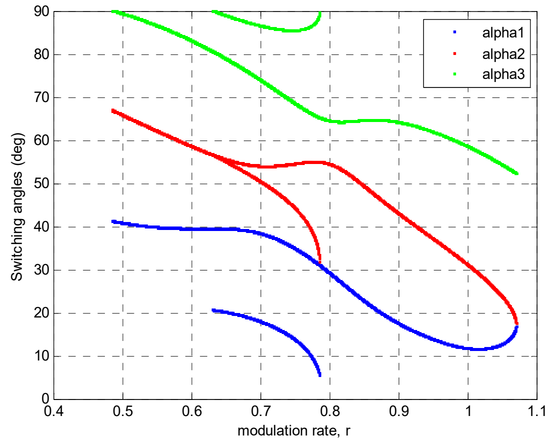
(c) Four Switching angles to eliminate harmonics h_5, h_7 and h_{11}. S_i = [1, 1, -1, 1]

Fig. 7 Switching angles for five level inverter versus modulation index: (a) two angles (b) three angles (c) four angles

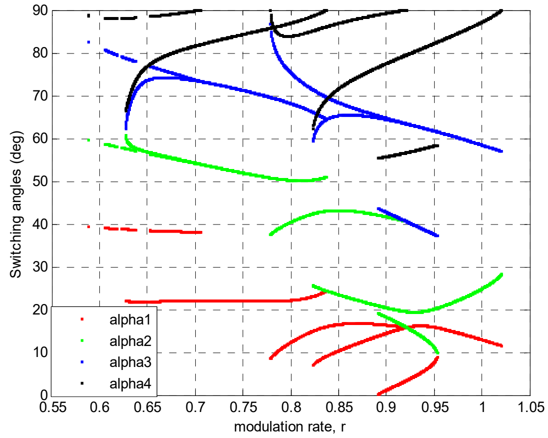
C. Three-Phase Seven Level Inverter

Like parts 4.1 and 4.2, it is chosen to eliminate harmonics (h_5, h_7) and (h_5, h_7, h_{11}).

The inverter delivers seven levels of voltage (3Uc, 2Uc,Uc, 0, -Uc, -2Uc, -3Uc). The number of level (N = 7) imposes a minimal number of angles equal to three. That permits to eliminate two harmonics (h_5, h_7).



(a) Three switching angles to eliminate h_5 and h_7. S_i = [1, 1, 1]



(b) Four switching angles to eliminate harmonics h_5, h_7 and h_{11}. S_i= [1, 1, 1, -1]

Fig. 8 Switching angles for seven level inverter versus modulation index: (a) three angles (b) four angles

D. Discussion

From the simulation results, it is found that:

- After some generations (or iterations), the right solution is found with the right choice of FA parameters (α, β_0, γ, d, n).
- The system (8) has a distinct interval in solutions of $\boldsymbol{r}$ for different $\boldsymbol{C}$.
- The variation in values of the angles is not a linear function of $\boldsymbol{r}$.

The FA gave good results for solving the nonlinear algebraic system (8) where the fitness is zero (zero with a precision of e = 10^{-4}). When the system (8) is changed, i.e. the number of angles (C), the number of levels (N) and the harmonics to be eliminated, it may be necessary to adjust the parameters of FA (α, β_0, γ, d, n).

For the case of a three-phase multilevel inverter, there are interval or were found double and even triple solutions (Figs. 5 (b), 7 (b), and 8 (b) and it was also found that there are points, where there are two angles α_i and $\alpha_{i+1,}$ which have the same value (double value).

Note that the system (8) sometimes not allow solution for some value of r (Fig. 5 (a) for r > 1.2 and Fig. 7 (b) for r < 0.52 and r > 097). Because of this last remark, there will be no switching in the switch and the method gives values that do not respect the condition (9) and Fitness takes a value near zero but not zero. Sometimes, it has only one solution to a value r especially for the case (C_angle = N_level) (Figs. 5 (a) and 7 (a)).

For a reasonable solution of the system (8) for small values of r (r < 0.5), it is better to apply the strategies to a lower number of levels.

Fig. 6 shows the variation of THD and the fundamental harmonic versus modulation index (r) for three-level inverter. (C = 3) to eliminate h_5 end h_7. THD decreases. The modulation index ***r*** is linear (***r*** = 0 to 1,2). Beyond this interval, the system does not have solutions according to the condition (9).

The harmonics h_{11}, h_{13}, h_{17} and h_{19} have the most significant amplitudes because the conservation of energy (the energy of the harmonics eliminated will be transmitted to no eliminated harmonics). But, they will be filtered by the load (the motor).

The FA has the advantage to find the correct solution even if it takes fireflies of the first iteration randomly, the solution will converge to the correct solution as a Genetic Algorithms [7] and PSO, contrary to the Newton-Raphson method which is most commonly used [10].

V. Experimental Results

The constructed prototype hardware with the test work-bench is shown as a photograph in Fig. 9. The control circuit and power circuit of the proposed inverter is designed and fabricated. The two DC voltages are set to 30V and the resistive load is set to 100 Ω. Power switches are chosen IGBT and Controller Board is dSpace DS1103.

The FA is applied successfully on a three-level three phase NPC inverter [11], [12]. The switching angles are calculated in off-line for different operating conditions. Real-Time Windows Target of MATLAB/Simulink is used to generate the gating pulses.

Fig. 11 shows the phase voltage of the output in r = 0.8. Figs. 10 and 12 show simulation and experimental results respectively for three-level three phase NPC inverter to eliminate harmonics h_5, h_7 and h_{11} in r = 0,8 and S_i = [1, -1, 1, -1]. Optimal switching angles in this case are selected as α_1 = 12.6079°, α_2 = 61.0159°, α_3 = 69.9154° and α_4 = 78.0880°.

As can be seen in Figs. 10 and 12, the harmonics h_5, h_7, h_{11} and the triplen harmonics are zero. The voltage waveforms and Harmonic Spectrums in the both figures are almost the same with a smallerror. In fact, this error is resulted from several constraints such as error of measurement instruments, non-ideal DC source, IGBT characteristics.

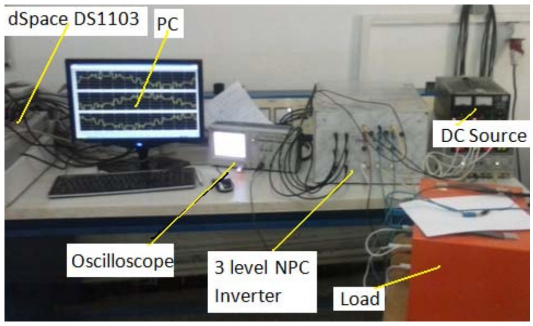


Fig. 9 Test work-bench

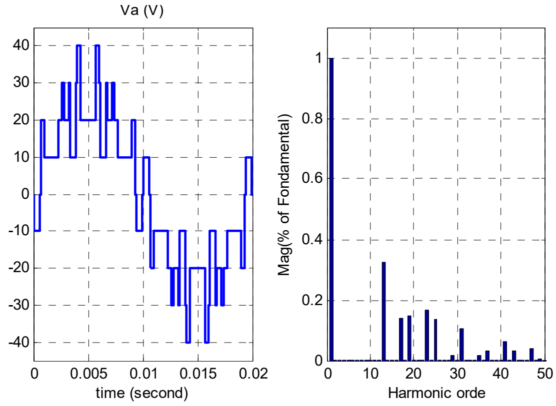


Fig. 10 Simulation results for three-level inverter (r = 0.8): Phase voltage (Va) and the Harmonic Spectrum

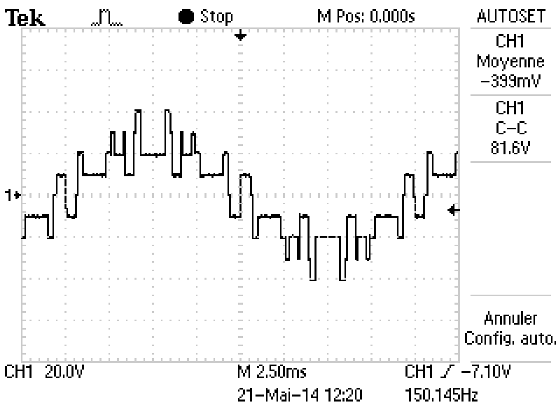


Fig. 11 Phase voltage (Va) of the used inverter

VI. Conclusion

In this paper, the FA and the SHEPWM strategy are presented. This paper demonstrated the ability to use the FA in the search for solutions for nonlinear equations systems. FA are used to find the switching angles for harmonic elimination technique applies to multilevel inverters

The results obtained are valid for all voltage Three-phase multilevel inverters with three, five or seven levels with different structures. the system of nonlinear equations of C equations can be generalized for N-level inverter to eliminate C-1 harmonics.

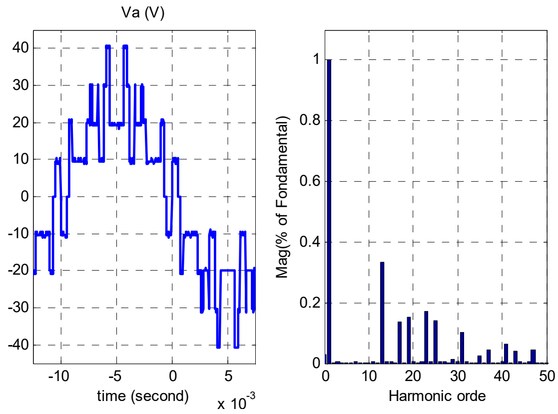


Fig. 12 Experimental results (measurements data) for three-level inverter (r = 0.8): Phase voltage (Va) and the Harmonic Spectrum

It is noted that the system (8) admits solutions in a small range and not for any value of r and sometimes admits several solutions for the same value of r.

The FA has the advantage to find the correct solution if the system admit correct solution. Even if it takes the population of fireflies of the first iteration randomly, the population of the fireflies (solutions) will converge to the correct solution.

The experimental results validate the simulation results.

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