Harmonic elimination in diode-clamped multilevel inverter using evolutionary algorithms

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A B S T R A C T

This paper describes two evolutionary algorithms for the optimized harmonic stepped–waveform technique. Genetic algorithms and particle swarm optimization are applied to compute the switching angles in a three-phase seven-level inverter to produce the required fundamental voltage while, at the same time, specified harmonics are eliminated. Furthermore, these algorithms are also used to solve the starting point problem of the Newton-Raphson conventional method. This combination provides a very effective method for the harmonic elimination technique. This strategy is useful for different structures of seven-level inverters. The diode-clamped topology is considered in this study.

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1. Introduction

In recent years, there has been a growing interest in power electronic systems due to the increasing utilization of electrical and electronic equipment, not only for industrial but also for commercial and residential applications. Another reason is the interest in improving the efficiency of systems, besides the expansion of the application of renewable energies. This growing demand has favored the development of new power electronic devices, as well as novel power converter topologies.

In 1981, the earliest multilevel inverter was introduced by Nabae et al. [1]. Since then, the multilevel voltage inverter has been receiving wide attention in research and high power applications. Compared with the traditional two-level voltage inverter, the main advantages of the multilevel inverter are a smaller output voltage step, lower harmonic components, a better electromagnetic compatibility and lower switching losses [2]. Multilevel converters are the most attractive technology for the medium to high voltage range, which includes motor drives, power distribution, power quality and power conditioning applications.

There are several types of multilevel inverters but the one considered in this work is the diode-clamped multilevel inverter (DCMI). Various modulation and control strategies have been devised for controlling the voltage source DCMI. One frequently studied optimal control method is the harmonic elimination technique. It implies the complete elimination of some low-order harmonics. Several optimization methods have been proposed for the harmonic elimination [3], in particular, the approach given in [4,5] produces a system of nonlinear transcendental equations that requires complex resultants and a symmetric polynomials theory.

Previous work in this area focused primarily on the cascade multilevel inverter. It is shown in [6–8] that the problem of harmonic elimination is converted into an optimization task using binary coded genetic algorithms (GA). Genetic algorithms are one such technique that received at lot of attention in recent literature, owing to its popularity to the possibility of searching irregular and high-dimensional solution spaces.

This paper investigates the harmonic suppression in the seven-level diode-camped inverter with real coded genetic algorithms and proposes a new method based on particle swarm optimization (PSO). PSO is a recent competitive optimization tool for nonlinear optimization problems. In addition, hybrid evolutionary algorithms that combine GA or PSO with the conventional Newton-Raphson methods (NR) are employed to achieve the solution of harmonic elimination with great precision.

2. Structure of the seven-level diode-clamped inverter

Fig. 1 shows the basic structure of a three-phase seven-level diode-clamped inverter driven induction motor. It is assumed that the dc voltage sources are all the same. This structure generates seven voltage levels in each output phase, and is generally applied to high-power applications because of its abil-
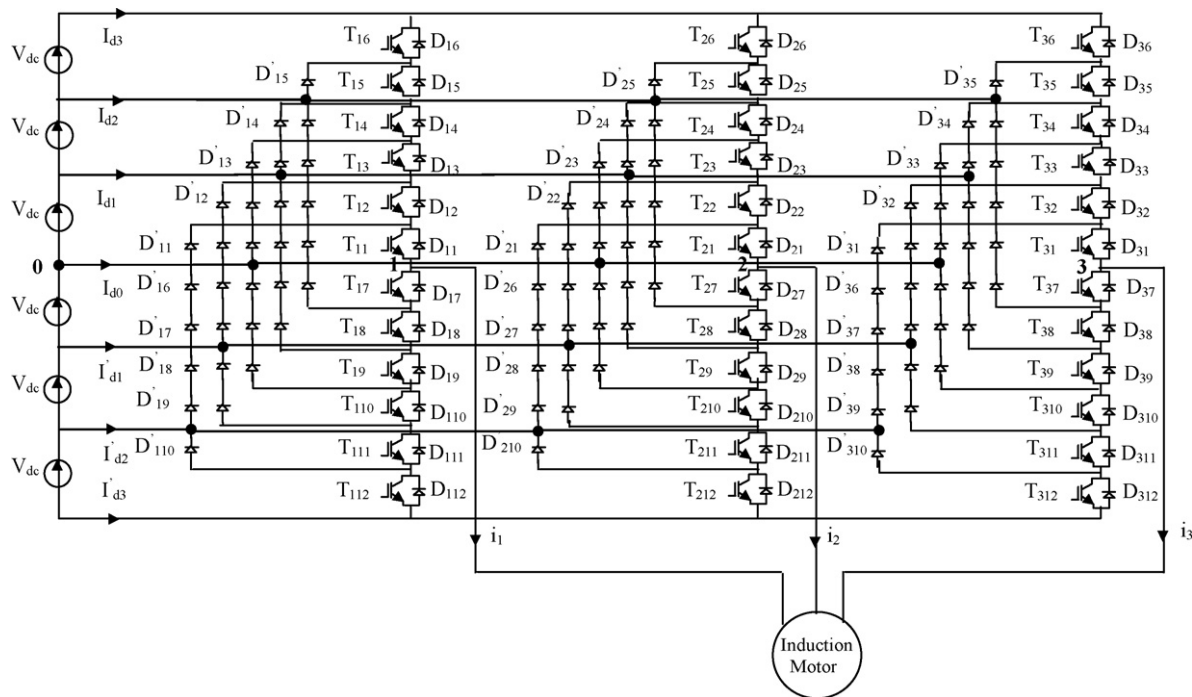
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Fig. 1. Configuration of the seven-level diode-clamped inverter.

ity to operate with larger voltages than the classical two-level inverter.

2.1. Control of the inverter with step pulses

The seven-level inverter divides the main dc supply into six dc sources which are used to synthesize an ac voltage into a staircase approximation of the desired sinusoidal waveform, as shown in Fig. 2.

To explain how the staircase voltage is synthesized, point 0 is considered as the output-phase reference point. Using the seven-level inverter shown in Fig. 1, there are seven switch combinations that generate seven voltage levels across 1 and 0. Table 1 shows the phase voltage levels and their corresponding switch states. From Table 1, state 1 indicates that the switch is on and state 0 indicates that it is off. In each phase leg, a set of six adjacent switches is on at any given time. There are six complementary switch pairs in each phase.

2.2. Fourier series analysis

With the equal amplitude of all dc sources, the expression of the amplitude of the fundamental and all harmonic contents, when
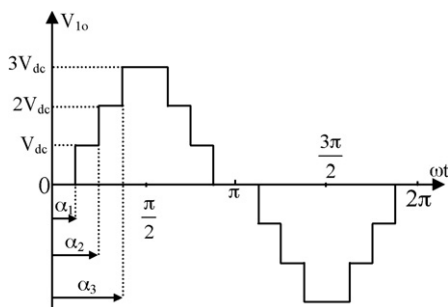

Fig. 2. Quarter-symmetric stepped-voltage waveform of the seven-level inverter.

Table 1
Switching states and output voltage of the seven-level diode-clamped inverter

Output voltage V_{1o}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{110}	S_{111}	S_{112}
$+3V_{dc}$	1	1	1	1	1	1	0	0	0	0	0	0
$+2V_{dc}$	1	1	1	1	1	0	1	0	0	0	0	0
$+V_{dc}$	1	1	1	1	0	0	1	1	0	0	0	0
0	1	1	1	0	0	0	1	1	1	0	0	0
$-V_{dc}$	1	1	0	0	0	0	1	1	1	1	0	0
$-2V_{dc}$	1	0	0	0	0	0	1	1	1	1	1	0
$-3V_{dc}$	0	0	0	0	0	0	1	1	1	1	1	1

normalized with respect to V_{dc} are given as [9,10]:

$$H_n(\alpha) = \begin{cases} \dfrac{4}{\pi n} \sum_{k=1}^{3} \cos(n\alpha_k) & \text{for odd } n \\ 0 & \text{for even } n \end{cases} \quad (1)$$

where α_k is the switching angles.

The Fourier series of the quarter-wave symmetric multilevel waveform is written as follows:

$$V_{10}(\omega t) = V_{dc} \sum_n H_n(\alpha) \sin(n\omega t) \quad (2)$$

where n is an odd harmonic order.

3. Problem formulation

The objective is to find the switching angles to force the components H_5 and H_7 to zero while keeping the relative fundamental component at a desired value:

$$H_1^{ref} = \frac{V_{ref}}{V_{dc}} \quad (3)$$

where V_{ref} is the reference output voltage.

This purpose is transformed into an optimization problem and is stated as follows:

Minimize the cost function:

$$\text{Fitness}(\alpha_1, \alpha_2, \alpha_3) = w_1|3M - H_1| + w_2|H_5| + w_3|H_7| \tag{4}$$

where M is the modulation index defined as follows:

$$M = \frac{V_{\text{ref}}}{3V_{\text{dc}}} \tag{5}$$

and w_i ($i = 1, 2, 3$) are positive weights. Thanks to them, a greater importance is given to the fundamental over the harmonic elimination. The choice is, in this case, $w_1 = 10$, $w_2 = 1$, $w_3 = 1$.

The correct solution must satisfy the basic constraint:

$$0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \frac{\pi}{2} \tag{6}$$

A full non linear multivariable problem has now been defined. The use of GA, PSO and mixed NR algorithms to solve it will be investigated.

4. Harmonic elimination using genetic algorithms

Genetic algorithms are powerful stochastic global search and optimization algorithms, based on the mechanics of natural selection and natural genetics. They have proven to be effective at solving a variety of complex problems that other conventional algorithms have solved with difficulties [11,12].

The analogy with biological processes gives a clear idea of how a genetic algorithm operates where mutation and crossover play a major role. Good solutions are selected and manipulated to achieve new and possibly better solutions. In each generation of the GA, the new solutions replace the solutions in the population that are selected for deletion.

The solution to the harmonic elimination problem is three switching angles α_1, α_2, α_3. Each switching angle is called a gene. A chromosome consists of all the genes and in this case there are three genes in one chromosome. Thus, each chromosome represents a possible solution to the problem. The population consists of a finite set of chromosomes.

The coding of individuals or chromosomes was originally done with strings of binary digits representing the genes put one aside the other. Now, real code algorithms are used and give more flexibility to manipulate and interact with the self-meaning vector of parameters without having to deal with a binary to decimal transformation.

The real code algorithms also offer the possibility of combination with classical optimization methods and lead to hybrid methods.

Various steps involved in real code GA approach for harmonic elimination describing how the GA is designed and applied to the present problem. The proposed pseudocode for a GA is as follows [12,13]:

Step 1: Create an initial population of N individuals with random angles that respect the constraints (6);

Loop

{

Step 2: Evaluate the fitness function for each individual according to equation (4);

Step 3: Order the *Nbest* ≤ *N* individuals from the best to worse. Individuals from 1 to *Nbest* are considered as able to reproduce;

Step 4:

For each individual from *Nbest* to *N* do:

Randomly select a number between 0 and 1: operation;

If *Operation < Crossover probability*

- Select two parents at random P_1 and P_2;

- *Offspring* = whole arithmetic crossover of the selected parents: a linear combination of P_1 and P_2;

Else if *Operation < Crossover probability + Mutation probability*

- Select one chromosome at random;

- *Offspring* = mutation of chosen chromosome;

Else

Offspring = mutation of the best chromosome;

End if

} Until the stop condition is reached

The stop conditions can be a fixed number of generations. We can also stop if the best fitness changes below a given rate.

5. Harmonic elimination using particle swarm optimization

The particle swarm optimization, first introduced by Kennedy and Eberhart, is one of the modern heuristic algorithms. It has roots in the birds flocking, fish schooling and swarming theory [14,15].

Step 1:

- Initialize the position $p(0)=[\alpha_1(0)\ \alpha_2(0)\ \alpha_3(0)]$ of each particle with random angles that respect the constraints (6);

- Initialize the velocities of all particles to zero;

- Initialize the *pbest*;

Loop

{

Step 2:

- Compute the *fitness$_i$* value of each particle i of the swarm using the cost function given by (4);

  If the *fitness$_i$* is better than its personal best fitness ever, then memorize this new personal best and its position *pbest$_i$*;

- Set *gbest* position at where the best fitness of all particles was found;

Step 3:

For each particle:

- Calculate the new particle velocity according to equation (8);

- Update particle position according to equation (7);

} Until the termination conditions are met.

Scientists tried to simulate the social behavior of animals and their movement, by observing bird flocking choreography.

The main idea behind the PSO is to simulate the movement of a flock of birds (particles) seeking food. These birds are randomly initialized and freely fly across the search space. During flight, each bird updates its own velocity and its personal best position (*pbest*) with a lower objective function value. The updating policy drives the bird swarm to move toward the general best position (*gbest*). That is the overall best place found by one member of the swarm, and eventually all birds will gather at this position [12,16].

At each step, called epoch, if p_i is the current position of the particle in the swarm, its new position will be:

$$p_i^{\text{New}} = p_i + v_i^{\text{New}} \cdot \Delta t \tag{7}$$

where v_i^{New} is the new velocity of each particle i of the swarm. It is updated by:

$$v_i^{\text{New}} = w \cdot v_i + p\_incr \cdot rand \cdot (pbest_i - p_i) + g\_incr \cdot rand \cdot (gbest - p_i) \tag{8}$$

where *rand* is an uniformly distributed random number in [0,1], w a weight coefficient introduced to give some inertia to the movement, so that the bird cannot change direction abruptly. p_incr and g_incr are increment amounts by which the speed can be changed according to the personal best position and the general best position of the swarm. $pbest_i$ is the personal best position of particle i. *gbest* is the general best position of the swarm.

The pseudocode for a PSO adopted in a harmonic elimination problem is given below [12,13]:

Note that to respect condition (6), the solutions must be forced to stay in the compulsory order. Only ordered solutions are retained.

6. Hybrid (GA, PSO)-Newton Raphson method

The successful application of Newton's method to harmonic elimination equations depends on a clever choice of the starting point. It is possible to calculate a good initial guess of solution with a few iterations using evolutionary algorithms. The resulting solution is considered as the starting point of Newton's algorithm.

To control the fundamental amplitude and to eliminate harmonics in the seven-level inverter, three nonlinear equations can be set up as follows [9]:

$$\begin{aligned} \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) &= \frac{3\pi}{4}M \\ \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) &= 0 \\ \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) &= 0 \end{aligned} \tag{9}$$

This system of equations can be rewritten in the following matrix format:

$$g(\alpha) = H \tag{10}$$

where:

$$g(\alpha) = \begin{pmatrix} \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) \\ \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) \\ \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) \end{pmatrix}$$

and $\alpha = [\alpha_1 \quad \alpha_2 \quad \alpha_3]$, $H = \left[\dfrac{3\pi}{4}M \quad 0 \quad 0 \right]$

To solve the switching angles of nonlinear Eq. (9), the hybrid method is applied. For a given value of M, this method solves the equations iteratively in the following sequence:

Step 1:

Generate an adequate starting point using the GA or PSO algorithms. Assume that:

$$\alpha^{(k=0)} = \begin{bmatrix} \alpha_1^{(0)} & \alpha_2^{(0)} & \alpha_3^{(0)} \end{bmatrix}$$

Loop
{

Step 2:

Linearization of equation (10) in respect to $\alpha^{(k)}$ as follows:

$$J(\alpha^{(k)})d\alpha^{(k)} + g(\alpha^{(k)}) = H \tag{11}$$

Where:

$$d\alpha^{(k)} = \begin{bmatrix} d\alpha_1^{(k)} & d\alpha_2^{(k)} & d\alpha_3^{(k)} \end{bmatrix}$$

and $J(\alpha^{(k)})$ is the Jacobian matrix of $g(\alpha^{(k)})$ given by:

$$J(\alpha^{(k)}) = \begin{bmatrix} -\sin(\alpha_1^{(k)}) & -\sin(\alpha_2^{(k)}) & -\sin(\alpha_3^{(k)}) \\ -5\sin(5\alpha_1^{(k)}) & -5\sin(5\alpha_2^{(k)}) & -5\sin(5\alpha_3^{(k)}) \\ -7\sin(7\alpha_1^{(k)}) & -7\sin(7\alpha_2^{(k)}) & -7\sin(7\alpha_3^{(k)}) \end{bmatrix} \tag{12}$$

Step 3: Solving the linear model (12) for $d\alpha^{(k)}$:

$$d\alpha^{(k)} = J^{-1}(\alpha^{(k)})(g(\alpha^{(k)}) - H) \tag{13}$$

The Jacobian matrix is assumed nonsingular at each iteration k.

Step 4: Updating the value of α.

$$\alpha^{(k+1)} = \alpha^{(k)} + d\alpha^{(k)} \tag{14}$$

$k = k + 1$;

} Until tolerance is reached;

A NR can also be implemented without knowing the explicit analytical form of the Jacobian matrix (12) by only approaching the J by derivating.

7. Simulation results

The above-mentioned algorithms are employed to compute switching angles α_i ($i = 1, 2, 3$). The three switching angles are calculated offline to eliminate harmonics for each modulation index M. The parameter M was incremented in step of 0.001.
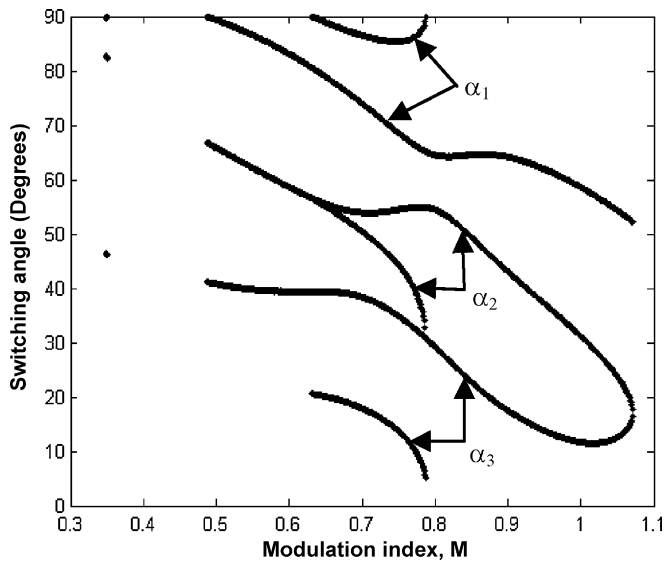
Fig. 3. Switching angles α_1, α_2 and α_3 versus the modulation index (GA algorithm).
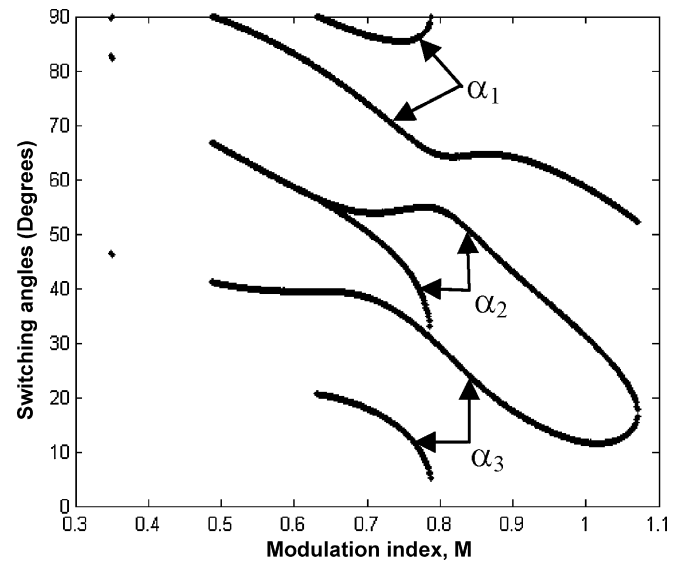

Fig. 5. Switching angles α_1, α_2 and α_3 versus the modulation index (PSO algorithm).

Figs. 3 and 4 show the optimum switching angles computed by GA and the cost function as a function of the modulation index. The parameters selected for the implementation of GA are: the population size = 100, the number of generations = 100, the crossover probability = 0.33 and the mutation probability = 0.33.

It has been observed that the maximum modulation index in this case is 1.07. Above this index, no harmonic elimination solution exists.

Similarly, Figs. 5 and 6 show the set of switching angles and the cost function when a PSO algorithm is used. The program is run for 20 particles with $w = 0.75$, $p\_incr = 1.8$ and $g\_incr = 1.8$. As seen in Figs. 4 and 6, any solution that yields a cost function lower than 0.001 is accepted. There is a double solution when M is between 0.632 and 0.787.

It is possible to observe how the swarm particles move over the search space using self developed tools that can be downloadable and used under GPL licence from [17]. Figs. 7 and 8 show how the particles can be observed, epoch by epoch, or in an animated mode.

Each particle appears as a triangular 3D fly with an arrow in front representing its actual speed.

While in animation mode, one can see them evolving in the search space, looking for the global minima. One can choose a particular particle which will appear in brown. The particle that holds the global best appears in red. Other particles appear in pink with a blue speed arrow. One can display a red target showing the global best position and a brown target showing the optimum that the swarm is looking for (Fig. 8). This tool allows the study of the PSO behavior on three variables optimization problem.

A greater precision in switching angles computation can be achieved by using hybrid methods. Figs. 9–12 show the outcomes obtained by the Newton-Raphson method when the initial values of switching angles are calculated by the GA or PSO algorithms. In this case, only solutions which minimize the THD are retained.

It was found that the combination of GA with NR (with the chosen configuration) always gives solutions when varying M. On the other hand, PSO shows some difficulties while finding initial
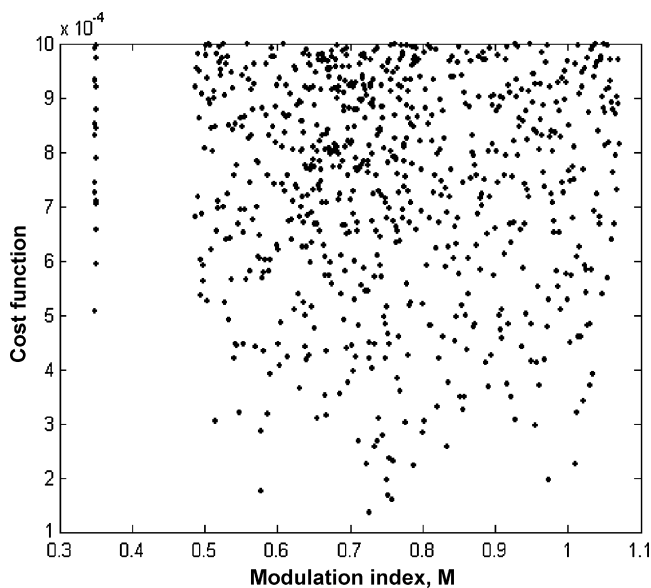

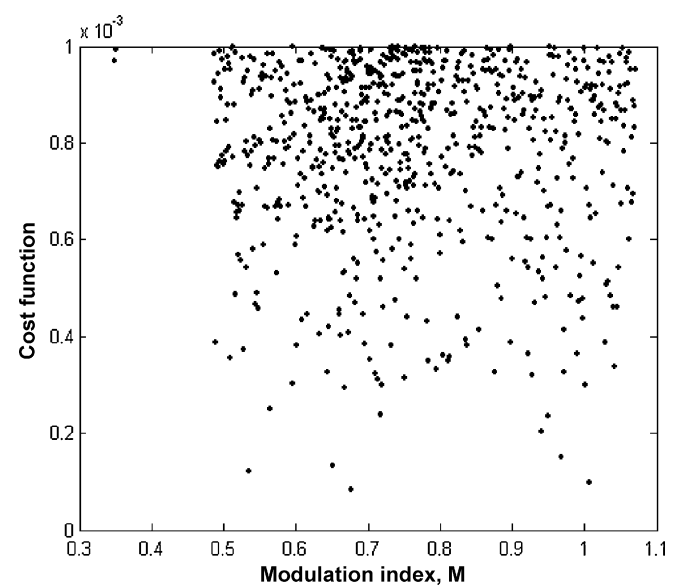**Fig. 4.** Cost function versus modulation index (GA algorithm).

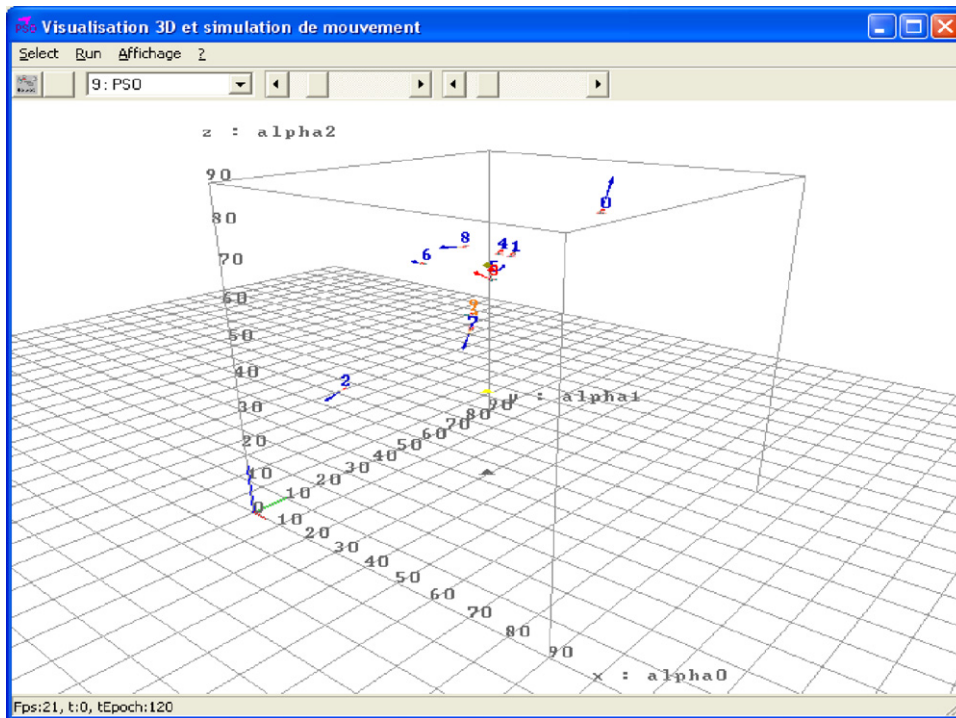**Fig. 6.** Cost function versus the modulation index (PSO algorithm).

Fig. 7. PSO 3D visualization tool showing the position and speed of the particles.

guesses or good starting points for a NR algorithm, leading it to non-convergence. One can of course; increase the swarm size or decrease the integration step that yields to the computation of the particles position, but the effort is to keep the same computing time for both the GA and PSO algorithm. The GA shows it superiority for this kind of problem. However, the PSO is very simple to implement.

Hybrid algorithms allow the use of the powerful NR method on the whole search space without manually finding initial guesses for the algorithm. This highlights the effectiveness of hybrid meth-

ods. Other forms of hybrid methods exist, of course; one would like to mention the PSO/GA one [18]. Though in this case, one must look for a robust method that precisely converges towards the solution.

Using the optimal switching angles calculated above, simulations have been conducted to verify that the fundamental frequency switching can achieve a high control performance. Fig. 13 illustrates the line-to-line voltage waveform when the modulation index is $M = 0.85$. Fig. 14 shows the first 100 harmonics (FFT) of the line
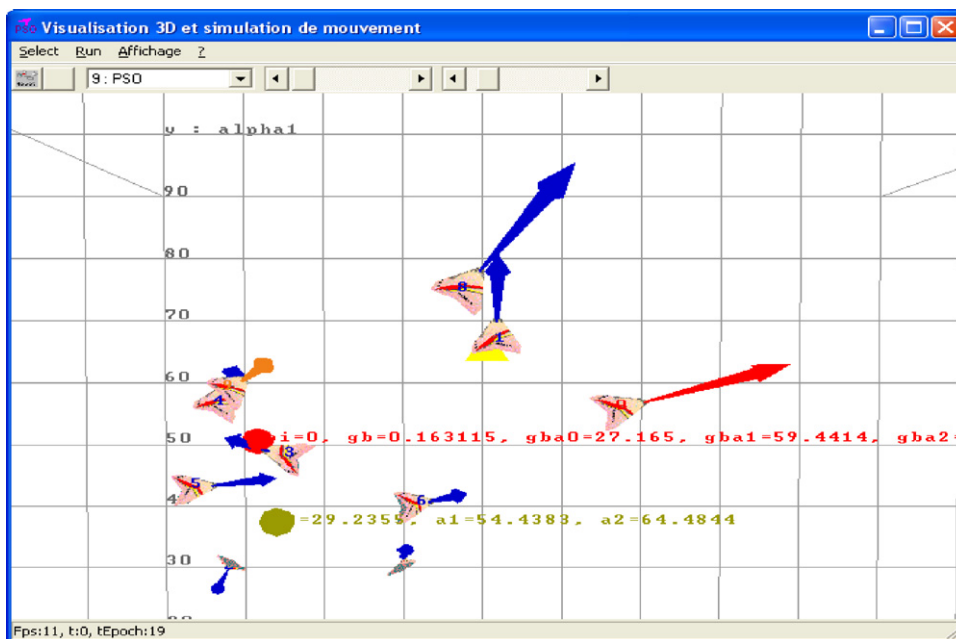

Fig. 8. Top view of the PSO 3D search space. The red target shows the global best position and the brown target is the optimum that the swarm is looking for. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
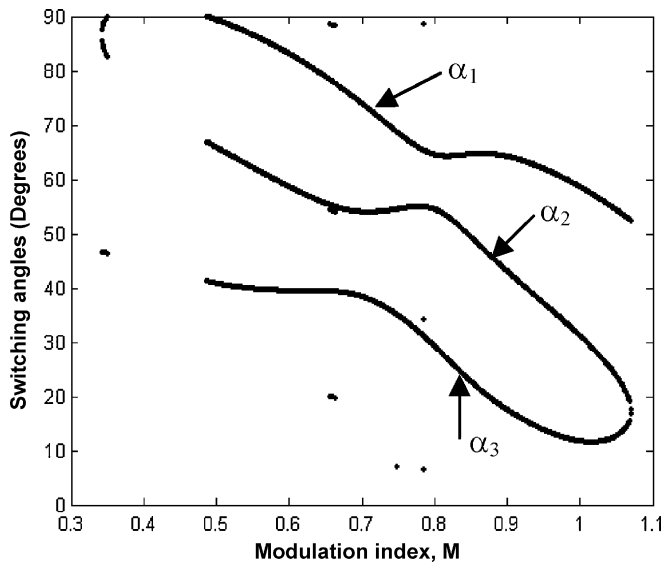
Fig. 9. Switching angles α_1, α_2 and α_3 versus the modulation index which give the smallest THD (Hybrid GA-NR algorithm).
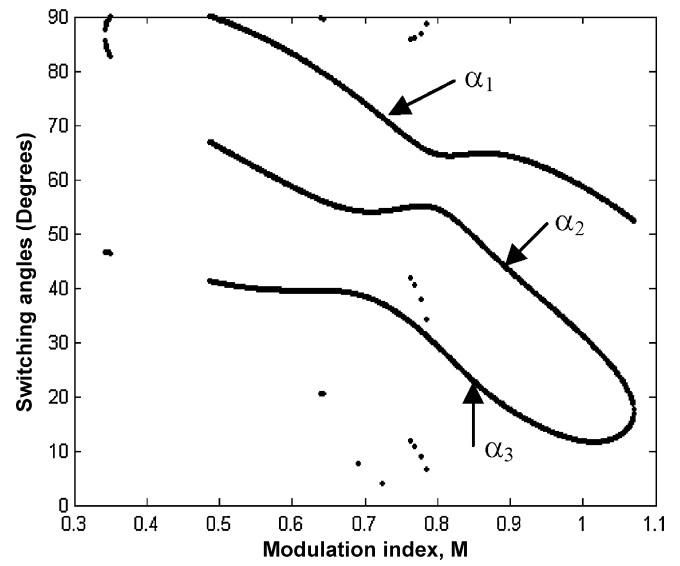

Fig. 11. Switching angles α_1, α_2 and α_3 versus the modulation index which give the smallest THD (Hybrid PSO-NR algorithm).

voltage. It is possible to verify in this later figure that the 5th and the 7th harmonics are negligible.

To indicate the quality of the output voltage, the total line voltage harmonic distortion is defined as follows:

$$THD(\%) = 100 \frac{\sqrt{\sum_{n=5}^{100} H_n^2}}{H_1} \qquad (15)$$

where n is an odd non triple number given by:

$$n = 6k \pm 1 \qquad (16)$$

Theoretically, to get the exact THD, infinite harmonics need to be calculated.

The THD is a suitable indicator used for measuring the harmonic quality of the output signals. However, there are several other parameters of performance mentioned in the literature. One of them is the harmonic distortion factor (HDF) which is a sim-

plified version of the THD [19]. The HDF gives the importance of the first two harmonics which are not eliminated compared with the fundamental one. The THD and the HDF are particular cases of the named weighted total harmonic distortion (WTHD) defined as [20,21]:

$$WTHD(\%) = 100 \frac{\sqrt{\sum_{n \neq 1} (w_n H_n)^2}}{H_1} \qquad (17)$$

Generally the load is equipped with a filter or it can behave as a filter that generates a more effective attenuation of higher-order harmonics. Thus, the WTHD is a measure of effectiveness in reducing unwanted harmonics without having to specify the values of a load filter. The WTHD is known especially by its two alternatives, one is called the first-order distortion factor (DF1) which approximates the load like a filter of the first order ($w_n = 1/n$). The second one is known as the second-order distortion factor (DF2) [22] quite simply the distortion factor (DF). DF indicates the
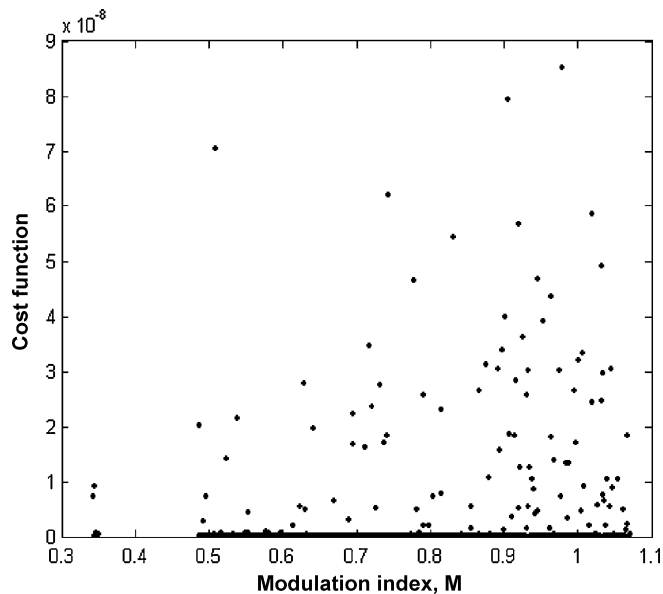

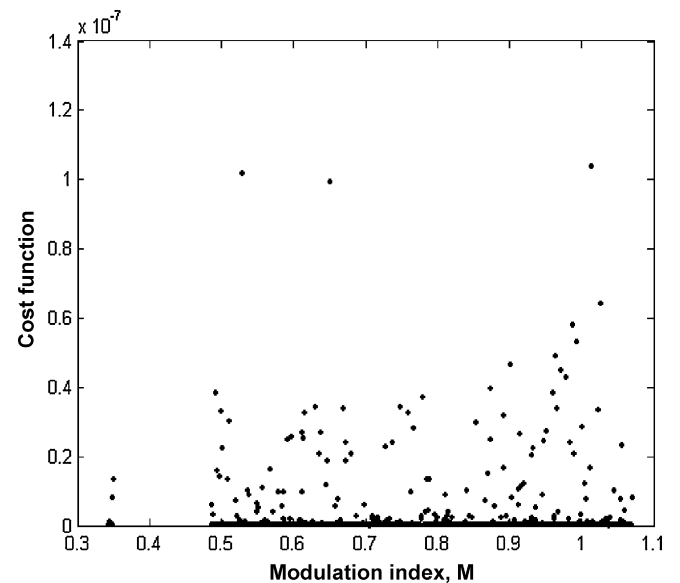**Fig. 10.** Cost function versus the modulation index (Hybrid GA-NR algorithm).

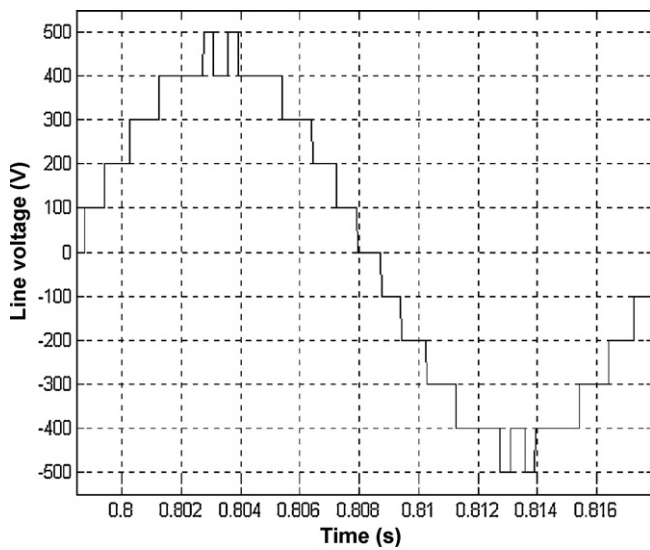**Fig. 12.** Cost function versus the modulation index (Hybrid PSO-NR algorithm).
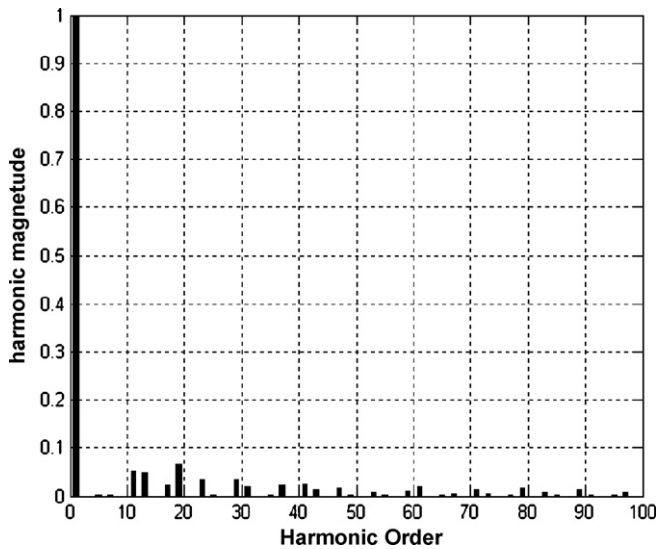
Fig. 13. Line voltage waveform for M = 0.85.

Fig. 14. Harmonic spectra of the line voltage for M = 0.85.
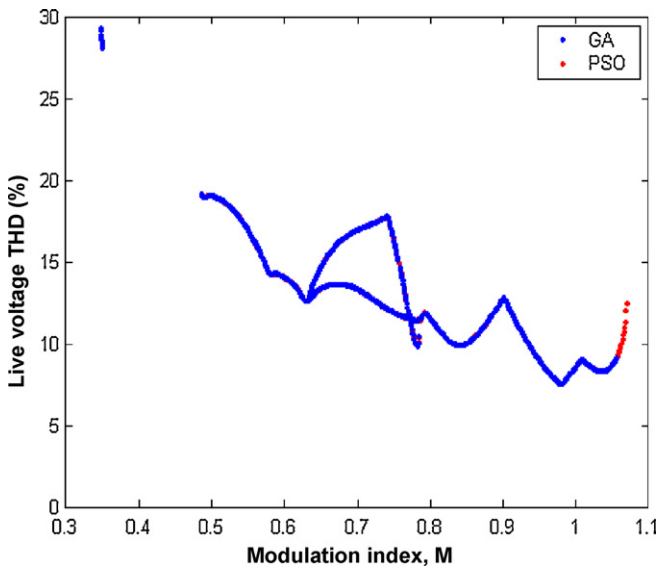

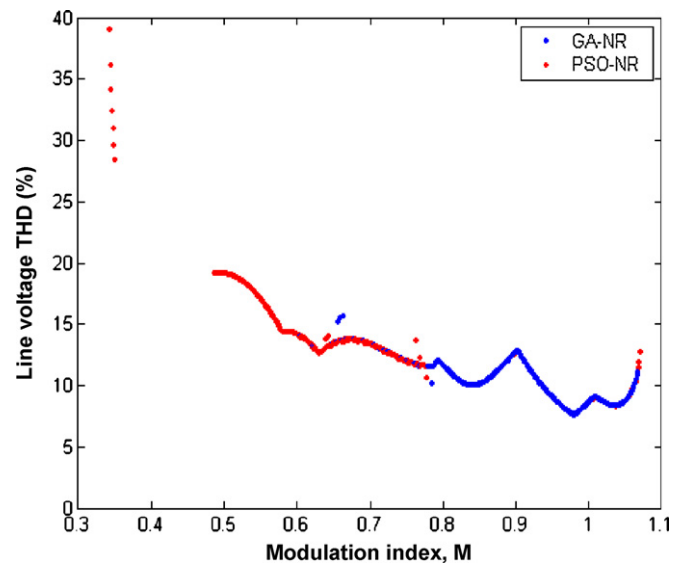Fig. 15. Line voltage THD versus the modulation index (GA or PSO algorithms).

Fig. 16. Line voltage THD versus the modulation index (Hybrid GA-NR or PSO-NR algorithms).

amount of harmonic distortion after the harmonics have been subjected to a second-order attenuation ($w_n = 1/n^2$) by the load filter. With $w_n = 1$, the THD is unable to take into account the effect of the load on the higher-order harmonics of the output signal. However, the THD remains very useful to make comparative studies between modulation methods or converters independently of the nature of the load, the reason for which it was adopted in this study. It should be noted that other parameters of individual evaluation of the harmonics exist. One can mention the harmonic factor, the individual distortion factor and the lowest-order harmonic [23].

The line voltage THD was computed according to (15) using the Fourier series data. Figs. 15 and 16 show the evolution of the line voltage THD as a function of the modulation index.

The multilevel inverter is connected to a 1.5 kW, 50 Hz three-phase induction motor. The simulation shows a direct start up under no load conditions. Simulation results of the overall sys-
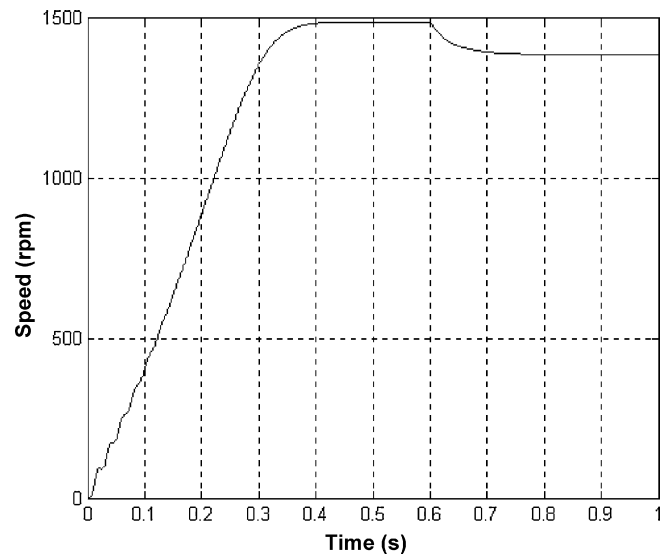

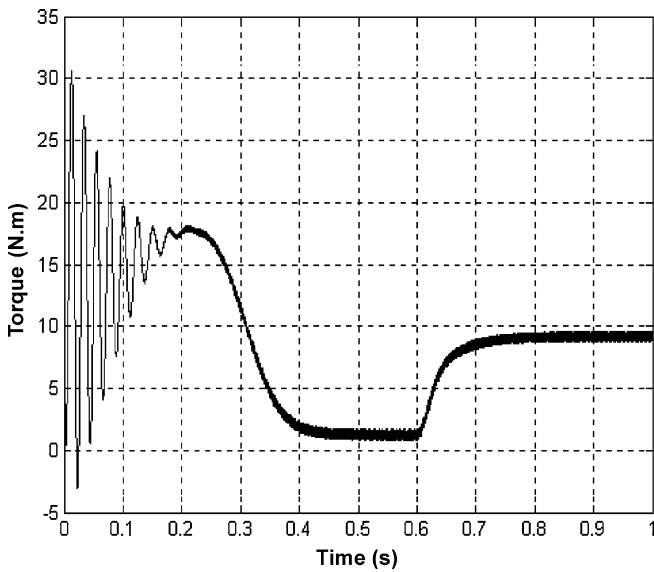Fig. 17. Machine speed on a direct start up (M = 0.85). A sudden load is applied at 0.6 s.

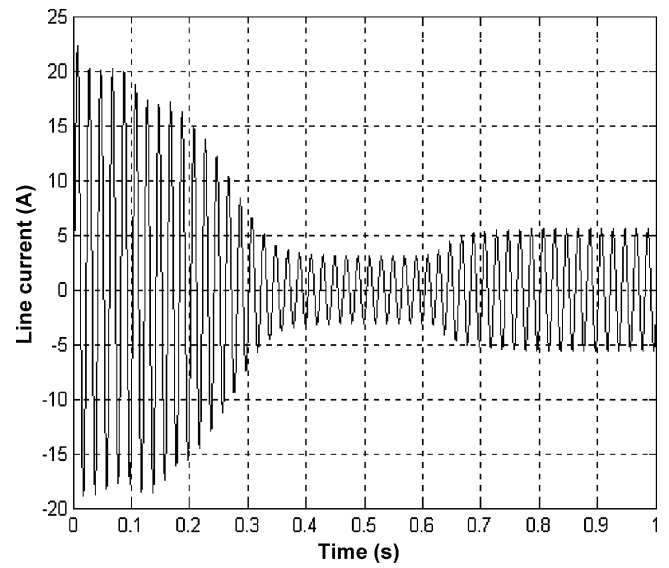**Fig. 18.** Machine torque on a direct start up ($M = 0.85$).

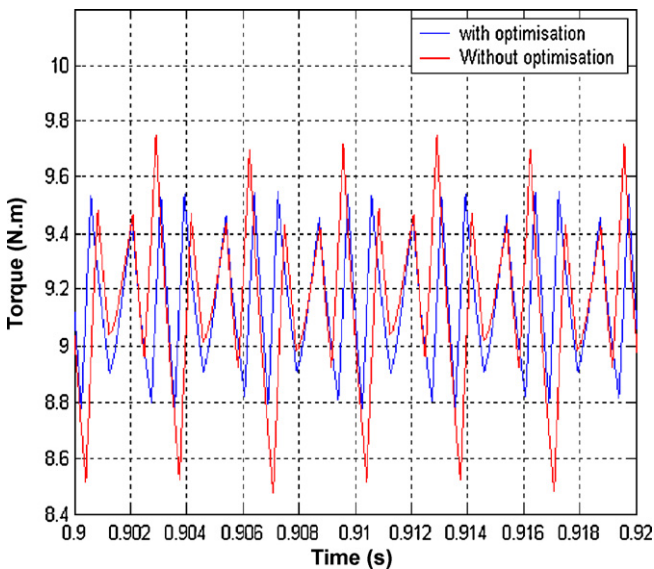**Fig. 20.** Machine phase current on a direct start up ($M = 0.85$).

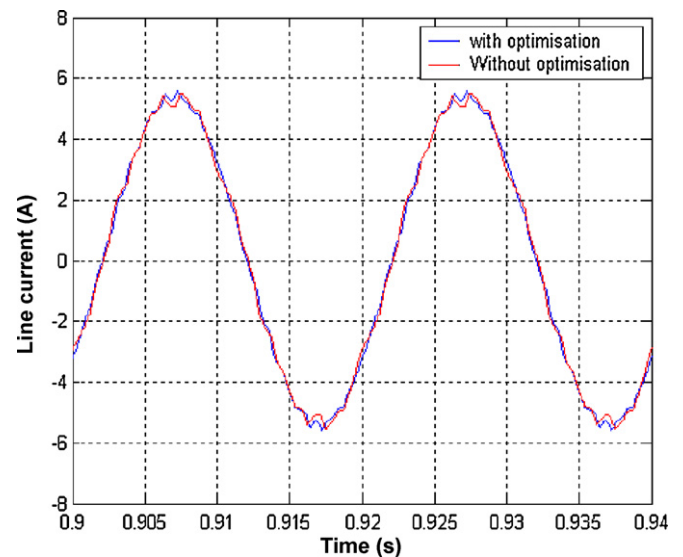**Fig. 19.** Torque ripple.

Fig. 21. Machine phase current with and without the harmonic elimination.

tem with a modulation index $M = 0.85$ and $V_{dc} = 100$ V are given in Figs. 17–21. A sudden load torque of 8 N m is applied at 0.6 s after the start up.

8. Discussion

It is clearly noticed that the number of solutions for each M increases with the reduction of the precision constraints by which solutions are calculated. It was shown that for a range of values of M, there were two different sets of solutions. In this situation, the solution which engenders the smallest THD will be adopted.

It can be seen, in Fig. 14, that the fifth and seventh harmonics are suppressed as expected and all the multiples of the third harmonics are eliminated in line-to-line voltage.

By observing Figs. 15 and 16, the line voltage THD increases slightly when the modulation index decreases. The induction machine filters the high frequency current components. Figs. 19 and 21 show that with the help of this harmonic elimina-

tion solution, the torque is less disturbed. The current waveform is also better than it would be using a non optimized stepped voltage waveform.

Overall results indicate that both the GA and PSO can be successfully used in the harmonic elimination problem.

9. Conclusion

In this paper, two evolutionary algorithms for harmonic elimination in a seven-level inverter have been proposed and evaluated. The study shows the implementation of algorithms and their effectiveness to find solutions to this complex non-linear optimization problem.

Compared to the GA, the PSO algorithm is much easier to implement and does not require several parameters to adjust.

It can be concluded that the PSO is also a promising tool for the power electronics converters optimization problem.

Newton's method tends to produce much better results when triggered from an initial starting point nearer to the optimal one. For this reason, the hybrid GA-NR and PSO-NR have been used to achieve an automatical and error free search for solution.

Moreover, the present study can be extended easily to any number of levels and can be applied to other multilevel inverter topologies.

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