A FIVE LEVEL NPC INVERTER CONTROLLED BY USING SHEPWM STRATEGY

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Abstract. *The object of this paper is to analyse the behaviour and the performances of a three-phase induction machine supplied with a five level neutral-point-clamped (NPC) inverter controlled by Selective Harmonic Eliminated Pulse-Width Modulation Technique (SHEPWM). First, the modelling of the inverter and the machine is presented. Thereafter, a theoretical study of the harmonics elimination strategy is detailed; where the genetic algorithm (GA) for elimination purposes is used. After that, this strategy is validated by simulation. Finally, a behaviour of the induction machine controlled with this inverter is presented.*

Keywords

Induction machine, NPC (Neutral Point Clamping), five level inverter, SHEPWM, genetic algorithm (GA).

1. Introduction

There are several structures of multi level inverter. In this work, the neutral-point-clamped (NPC) structure [1], [2], [3], [4] with five level has chosen.

For the control of the inverters, there are several strategies, most known are triangulo-sinusoidal strategy PWM, hysteresis PWM [2], [3], [4], [5], [6] and the Selective Harmonic Eliminated PWM technique (SHE PWM) [7], [8], [9], [10], [11], [12] which is the object of this article. This technique consists to calculate the switching moments of the switches of the inverter to have a sinusoidal form of current.

In order to improve much more quality of the output voltages, the SHEPWM technique will be presented to control five level inverter. This inverter supplies an induction machine.

2. Modelling of the Five Level NPC Inverter

Figure 1 represents the NPC structure of five level three-phase inverter. Thus, one will start by defining a total model of a leg (Fig. 2).

A topological analysis of one leg of the inverter shows seven configurations (Tab. 1 and the Fig. 3).

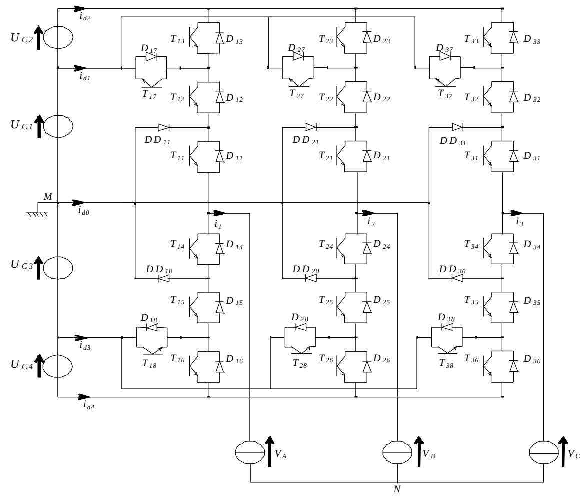


Fig. 1: NPC five level three-phase inverter structure.

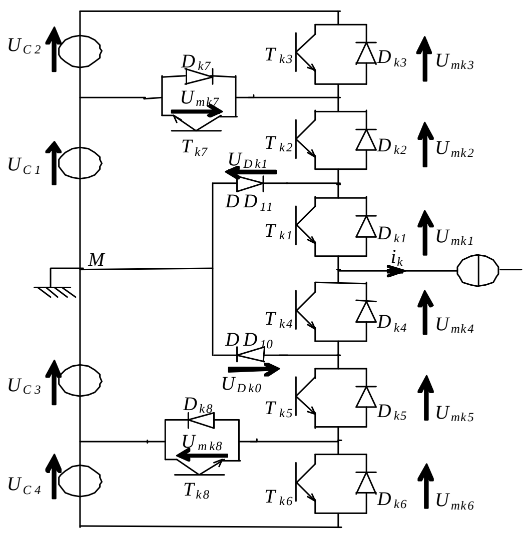


Fig. 2: Leg of the NPC five level inverter.

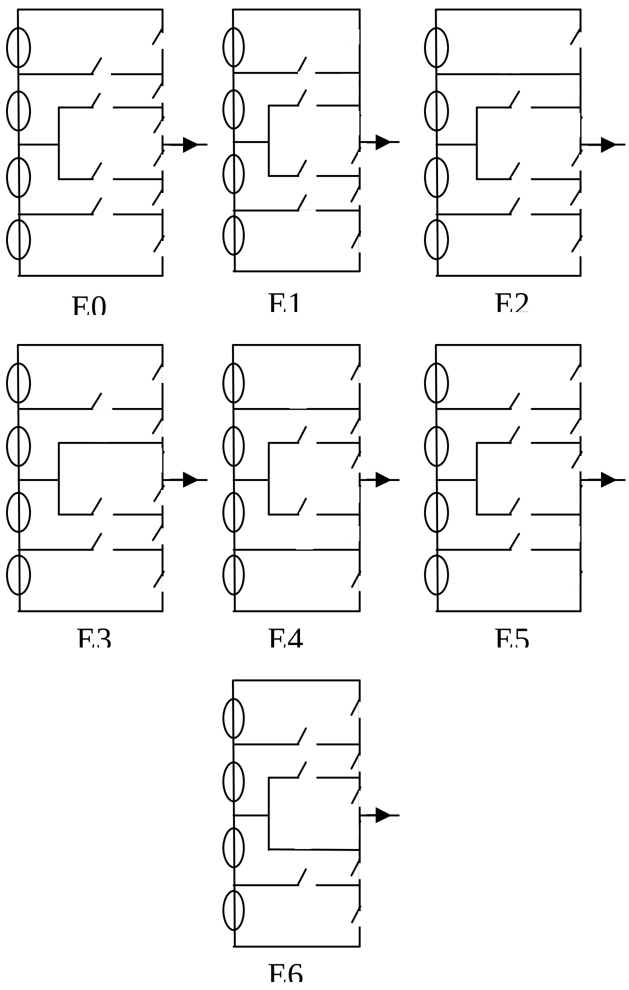


Fig. 3: Various possible configurations of a leg k.

Tab.1: Electric quantities for each configuration of a leg k.

Configuration	Electrical Quantities
E0	$I_k = 0$
E1	$V_{kM} = U_{c1} + U_{c2} = 2U_c$
E4	$V_{kM} = -U_{c3} = -U_c$
E3	$V_{kM} = 0$
E4	$V_{kM} = -U_{c3} = -U_c$
E5	$V_{kM} = -U_{c3} - U_{c4} = -2U_c$
E6	$V_{kM} = 0$

To avoid short-circuits of the voltage sources by conduction of several switches, and so that the converter is completely controlled, it is adopted a complementary control; the optimal control is defined as follows:

$$\begin{cases} F_{k4} = 1 - F_{k2} \\ F_{k5} = 1 - F_{k1} \\ F_{k6} = 1 - F_{k3} \end{cases} . \quad (1)$$

For a leg k, the connection functions of the half legs are expressed by means of the switches connection functions as follows where k=1, 2, 3:

$$\begin{cases} F_{k1}^b = F_{k1} \cdot F_{k2} \cdot F_{k3} \\ F_{k0}^b = F_{k4} \cdot F_{k5} \cdot F_{K6} \end{cases} . \quad (2)$$

The switches connection functions placed in parallel are defined as follows:

$$\begin{cases} F_{k7} = F_{k1} F_{k2} (1 - F_{k3}) \\ F_{k8} = F_{k4} F_{k5} (1 - F_{k6}) \end{cases} . \quad (3)$$

The potentials of nodes A, B and C referred to the medium point M in the case $U_{C1} = U_{C2} = U_{C3} = U_{C4} = U_C$ are given by the following system:

$$\begin{bmatrix} V_{AM} \\ V_{BM} \\ V_{CM} \end{bmatrix} = \begin{bmatrix} F_{17} + 2F_{11}^b - F_{18} - 2F_{10}^b \\ F_{27} + 2F_{21}^b - F_{28} - 2F_{20}^b \\ F_{37} + 2F_{31}^b - F_{38} - 2F_{30}^b \end{bmatrix} \cdot U_c . \quad (4)$$

The output line voltages at the boundaries of the load are given by the following system:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} F_{17} + 2F_{11}^b - F_{18} - 2F_{10}^b \\ F_{27} + 2F_{21}^b - F_{28} - 2F_{20}^b \\ F_{37} + 2F_{31}^b - F_{38} - 2F_{30}^b \end{bmatrix} \cdot U_c . (5)$$

3. Mathematical Model of Induction Machine

The model of the machine in a reference (d-q) related to the field is given by the system (6).

$$\left\{\begin{aligned}
&\frac{di_{ds}}{dt} = -\frac{1}{\sigma L_s}\left(R_s + R_r\frac{M_{sr}^2}{L_r^2}\right)i_{ds} + \omega_s i_{qs} + \\
&+\frac{M_{sr}R_r}{\sigma L_s L_r^2}\Phi_{dr} + \frac{M_{sr}}{\sigma L_s L_r}\Phi_{qr}\omega + \frac{1}{\sigma L_s}v_{ds} \\
&\frac{di_{qs}}{dt} = -\omega_s i_{ds} - \frac{1}{\sigma L_s}\left(R_s + R_r\frac{M_{sr}^2}{L_r^2}\right)i_{qs} - \\
&\frac{M_{sr}}{\sigma L_s L_r}\Phi_{dr}\omega + \frac{M_{sr}R_r}{\sigma L_s L_r^2}\Phi_{qr} + \frac{1}{\sigma L_s}v_{qs} \\
&\frac{d\Phi_{dr}}{dt} = \frac{M_{sr}R_r}{L_r}i_{ds} - \frac{R_r}{L_r}\Phi_{dr} + \omega_g\Phi_{qr} \\
&\frac{d\Phi_{qr}}{dt} = \frac{M_{sr}R_r}{L_r}i_{qs} - \omega_g\Phi_{dr} - \frac{R_r}{L_r}\Phi_{qr} \\
&\frac{d\omega}{dt} = \frac{p^2M_{sr}}{jL_r}\Phi_{dr}i_{qs} - \frac{p^2M_{sr}}{jL_r}\Phi_{qr}i_{ds} - \frac{f}{j}\omega - \frac{p}{j}C_r
\end{aligned}\right. \quad .(6)$$

With: $\sigma = 1 - \frac{M_{sr}^2}{L_s L_r}$.

4. Selective Harmonic Eliminated Pulse-Width Modulation Technique (SHEPWM)

It is a technique based on the generating of a succession of variable widths impulse to establish the wave of the inverter output voltage [7], [8]. Generally, in the case of a five level three-phase inverter there is:

- a double symmetry in voltage V_a, V_b and V_c compared to π/2 and π. Then the even order harmonics are null.
- a balanced three-phase system, then the amplitudes of the harmonics of the order multiple of three are null too.

This wave is characterized by the number *C* where *C* represents the number of switching angles per quarter of period. Whatever the ***C*** odd or even, ***C*** angles is enough to determine the width of the whole of the crenels; these switching angles are given in such way to eliminate certain harmonics. In this study we were interested to eliminate the first harmonics (5, 7, 11, 13, 17) which are most unpleasant for the ideal operation of the loads such as the electric motors.

Figure 4 illustrates an example of a generalized curve on first quarter of period of the output voltage V_{AM} delivered by the five level three-phase inverter with structure NPC.

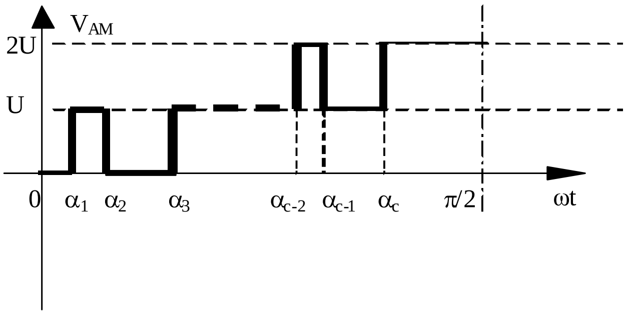


Fig. 4: The form of the first quarter of the output voltage V_{AM}.

Because of the characteristic of the wave which is symmetrical compared to the half and the quarter of 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, who only shows the existence of odd nature harmonics [8], [9], is given by

$$V_{AM}(\omega t) = a_n \sin(n\omega t), \quad (7)$$

where

$$\left\{\begin{aligned}
&a_n == \frac{4}{\pi}\int_0^{\frac{\pi}{2}} V_{AM}(\omega t)\cdot\sin(n\omega t)\, d\omega t \quad \textit{for odd } n \\
&a_n = 0 \quad \textit{for even } n\,. \\
&b_n = 0 \quad \textit{for all } n
\end{aligned}\right. \quad (8)$$

After integration, there will be the equation

$$a_n = \frac{4U}{n\pi}\left[S_1\cos(n\alpha_1) + S_2\cos(n\alpha_2) + .. + S_c\cos(n\alpha_c)\right]. \quad (9)$$

For *n* harmonic, the nonlinear system of equations is given by the following system:

$$\left\{\begin{aligned}
&S_1\cos(\alpha_1) + S_2\cos(\alpha_2) + \cdots + S_C\cos(\alpha_C) = \frac{\pi}{4}r \\
&S_1\cos(5\alpha_1) + S_2\cos(5\alpha_2) + \cdots + S_C\cos(5\alpha_C) = \frac{\pi}{4U_C}h \\
&\vdots \\
&\vdots \\
&S_1\cos(n\alpha_1) + S_2\cos(n\alpha_2) + \cdots + S_C\cos(n\alpha_C) = \frac{\pi}{4U_C}h_n
\end{aligned}\right. ,(10)$$

where:

- $r = \frac{h_1}{U_C}$ is the modulation index,
- ***n***: an odd number no multiple of three,
- U_C: supply voltage,

- $\boldsymbol{h_i}$: harmonic components (i[th] order harmonic) of the output voltage $\boldsymbol{U}$, where h_i=0; $i \neq 1$,
- $\boldsymbol{h_1}$: fundamental harmonic of the output voltage $\boldsymbol{U_C}$,
- $\boldsymbol{\alpha_i}$: switching angles,
- $\boldsymbol{S_i}$: the sign of cos equal to +1 or -1.

To eliminate (***C***-1) harmonics, it is necessary ***C*** angles and ***C*** equations for ***C*** unknown. The required solution must satisfy the following condition:

$$0<\alpha_1<\alpha_2<...<\alpha_{c-1}<\alpha_c<\frac{\pi}{2}. \tag{11}$$

The system (10) must be solved by a numerical method (Newton-Raphson) [8], [9], [11] or genetic algorithms [12], [13].

4.1. The Newton-Raphson Method

The resolution of the nonlinear equations system in order to find the appropriated switching angles is done by implementation of algorithm of the Newton-Raphson method.

The algorithm of Newton-Raphson's method can be shown as follows [8], [9]:

1) Guess a set of initial values for α with j=0. Suppose

$$\alpha^j=\left[\alpha_1^j,\alpha_2^j,...,\alpha_c^j\right]^T. \tag{12}$$

2) Calculate the value of

$$F(\alpha^j)=F^j. \tag{13}$$

F is the condensed vector format of nonlinear equation system (10).

3) Linear equation (13) about α^j

$$F^j+\left[\frac{\partial f}{\partial \alpha}\right]^j d\alpha^j=H. \tag{14}$$

With:

H is the amplitude of the harmonic components,

f is the functions connecting harmonics with switching angels,

and $d\alpha^j=\left[d\alpha_1^j \quad d\alpha_2{}^j \quad \cdots \quad d\alpha_c{}^j\right]^T$,

$$\left[\frac{\partial f}{\partial \alpha}\right]=\begin{bmatrix}\frac{\partial f_1}{\partial \alpha_1} & \frac{\partial f_1}{\partial \alpha_2} & \cdots & \frac{\partial f_1}{\partial \alpha_c}\\ \frac{\partial f_2}{\partial \alpha_1} & \frac{\partial f_2}{\partial \alpha_2} & \cdots & \frac{\partial f_2}{\partial \alpha_c}\\ \vdots & \vdots & \ddots & \vdots\\ \frac{\partial f_c}{\partial \alpha_1} & \frac{\partial f_c}{\partial \alpha_2} & \cdots & \frac{\partial f_c}{\partial \alpha_c}\end{bmatrix}.$$

4) Solve $d\alpha^j$ from (14) by

$$d\alpha^j=INV\left[\frac{\partial f}{\partial \alpha}\right]^j(H-F^j), \tag{15}$$

where $INV\left[\frac{\partial f}{\partial \alpha}\right]^j$ is the inverse matrix of $\left[\frac{\partial f}{\partial \alpha}\right]^j$.

5) As updated the initial values

$$\alpha^{j+1}=\alpha^j+d\alpha^j. \tag{16}$$

6) Repeat the process, equations (13) to (16), until $d\alpha^j$ is satisfied to the desired degree of accuracy.

4.2. Genetic Algorithm (GA)

As mentioned, the system equations are nonlinear. In order to solve these equations the genetic algorithm (GA), 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 GA a new set of strings, which are called chromosomes, are defined with improved fitness produced using genetic operators.

A more complete discussion of GAs including extensions o the general algorithm and related topics can be found in books by Davis [14], Goldberg [15], Holland [16], and Deb [17].

The structure of a simple GA consists mainly of three operators: a selection operator, a crossover operator which acts on a population of strings to perform the required reproduction and recombination, and a mutation operator which randomly alters character values, usually with a very low probability. The effect of these random alterations is to maintain diversity within the population, thereby preventing an early convergence of the algorithm to a possibly false peak.

Figure 5 represents the flowchart of genetic algorithm [12].

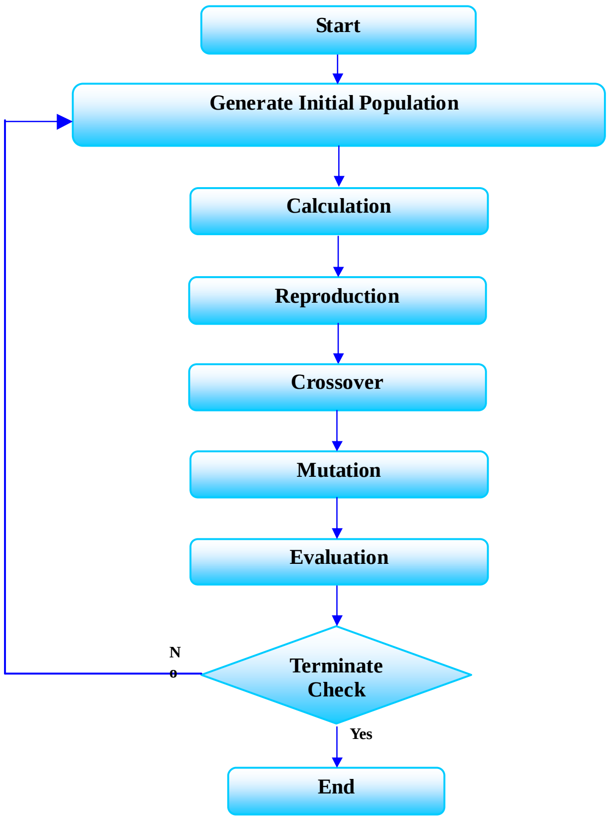


Fig. 5: Flowchart of genetic algorithm.

5. Simulation and Results

5.1. Calculation of Angles

To find the systems of equation which represent the different forms of voltage V_{AM}, it is necessary to replace the value of S_i by +1 for the angle where there is a level crossing of lower level to the upper levels, and -1 for the contrary case.

For example, to control the fundamental amplitude and to eliminate two harmonics (h_5 and h_7) in the five level inverter, three nonlinear equations (17) can be set ($C = 3$) with $S_1 = +1$, $S_2 = +1$ and $S_3 = -1$,

$$\begin{cases} \cos(\alpha_1) + \cos(\alpha_2) - \cos(\alpha_3) = \dfrac{\pi}{4} r \\ \cos(5\alpha_1) + \cos(5\alpha_2) - \cos(5\alpha_3) = 0 \\ \cos(7\alpha_1) + \cos(7\alpha_2) - \cos(7\alpha_3) = 0 \end{cases} . \tag{17}$$

Since the major problem of Newton-Raphson's method is the knowledge of switching angles [8]. If the choice of the starting point is bad, the method diverges from the correct solution. For that, value should be taken closer to the solution but this problem doesn't exist in the GA method.

In the case where the GA it used, Fig. 6 shows the behavior of the best solutions (α_1 α_1 α_3) in the population to eliminate the 5th and 7th order harmonics ($h_5 = 0$ and $h_7 = 0$) for $r = 0{,}8$ where the final solutions, in degree, are $\alpha_1 = 20{,}2697$ $\alpha_1 = 63{,}9642$ $\alpha_3 = 83{,}0880$.

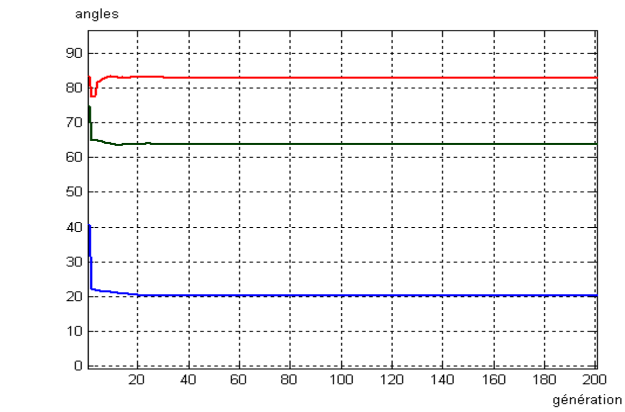
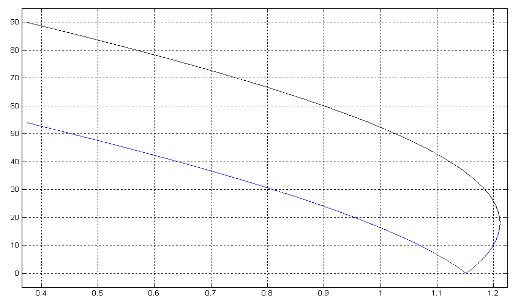
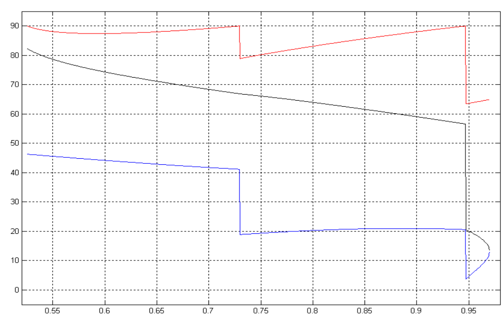


Fig. 6: The behavior of the best solutions (α_1 α_1 α_3) in the population to eliminate the 5th and 7th order harmonics for r=0,8.

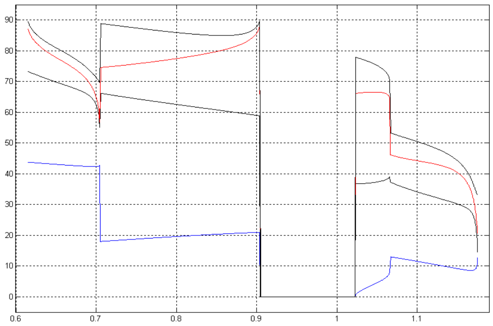
In this work the GA method is used to calculate the solutions. The results of programming giving the various switching angles and different value of C versus modulation index r are given in Fig. 7a, b, c, d, e.



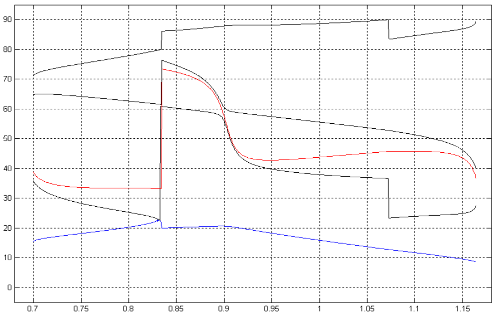
(a) C = 2 to eliminate (h_5)
$[S_1\ S_2] = [+1\ +1]$



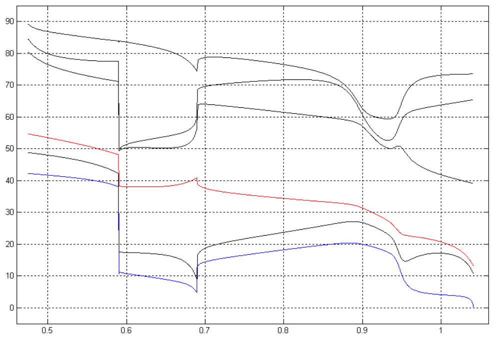
(b) C = 3 eliminate (h_5,h_7)
$[S_1\ S_2\ S_3\ ] = [+1\ +1\ -1]$



(c) C = 4 eliminate (h_5,h_7,h_{11})
[S_1 S_2 S_3 S_4] = [+1 +1 -1 +1]



(d) C = 5 eliminate (h_5, h_7, h_{11}, h_{13})
[S_1 S_2 S_3 S_4 S_5] = [+1 +1 +1 -1 +1]



(e) C = 6 eliminate (h_5, h_7, h_{11}, h_{13}, h_{17})
[S_1 S_2 S_3 S_4 S_5 S_6] = [+1 -1 +1 +1 -1 +1]

Fig. 7: The C Switching angles versus modulation index r to eliminate C-1 harmonics.

According to the results of simulation it noted that:

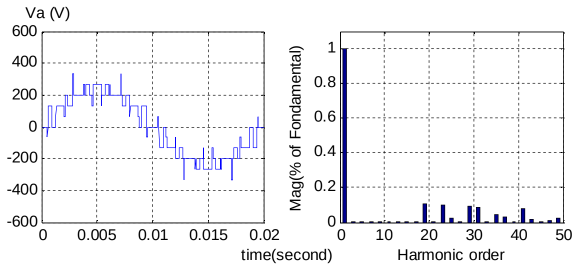
- the variation of the values of the angles is not linear according to ***r***,
- the system (10) has solutions in an interval distinct from ***r*** for various ***C***,
- there are points where there are two angles α_i and α_{i+1} have the same value, other hand have points where the angle have $\alpha_i \approx 0°$ or $\alpha_i \approx 90°$ that why the system has another value of angles where give the solution and by time it doesn't have solutions.

Because of this last mention, it will not have there commutation in the switches and the method gives values which do not observe the condition (11).

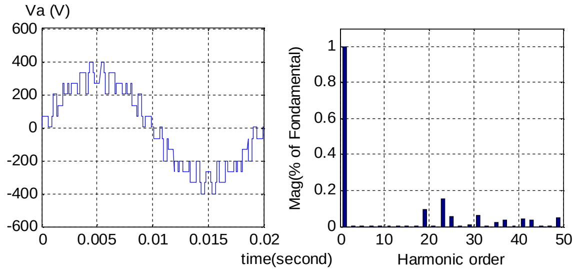
It is noted that: the system (10) sometimes doesn't have any solution for certain value of ***r*** (Fig. 7c) (r = 9,05:1,22) and sometimes, it doesn't have just one solution for a value of ***r***.

5.2. Inverter Control

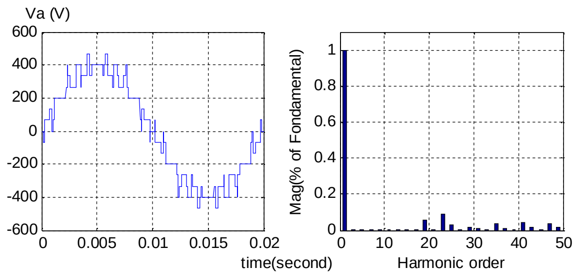
The inverter is controlled by the harmonic elimination strategy for **C** = 6 where they represent the output line voltage V_A and the frequency spectrum Fig. 8a, b, c. It is noticed that the first harmonics are nulls and the not eliminated harmonics have a value very significant but they are filtered by the load (the motor).



(a) r =0,6

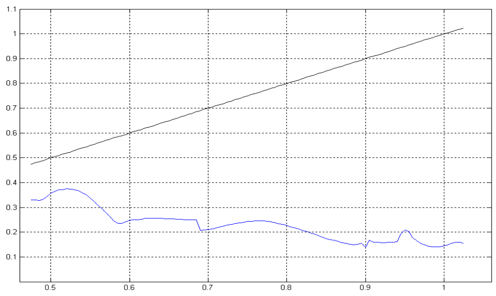


(b) r =0,8

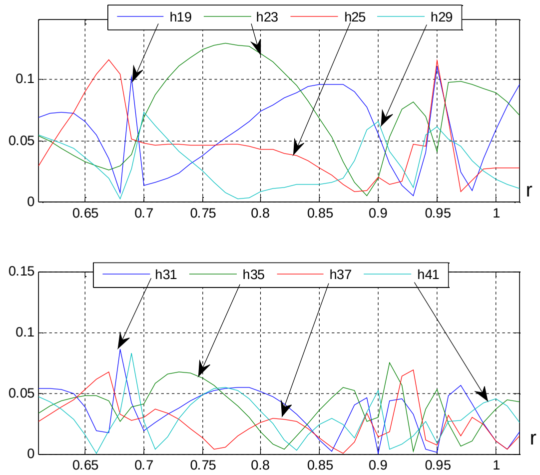


(c) r =1

Fig. 8: Line voltage and frequency Spectrum of the five level three-phase inverter.



(a) THD and h_1



(b) Harmonic amplitude versus modulation index r

Fig. 9: Characteristics of the line voltage (C=6, values in (PU)).

Figure 9a, b show the variation of THD and the harmonics principal versus to ***r***. The modulation index ***r*** is linear from ***r*** = 0,45 to 1,02. Beyond this interval, the system doesn't have solutions according to the condition of the angles (11).

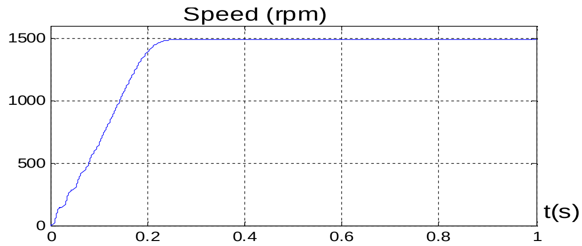
By observing Fig. 9a the line voltage THD increases slightly when the modulation index decreases. The induction machine filters the high frequency current components.

The 19^{th}, 23^{th} , 25^{th} and 29^{th} order harmonics have the most significant amplitudes because the conservation of energy (the energy of the harmonics eliminated to be transmitted to harmonics not eliminated).

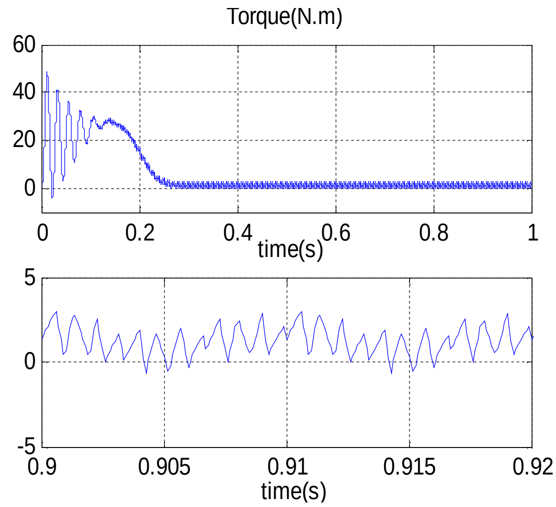
5.3. Power Supply of the Induction Machine

The five level NPC inverter is connected to a 1,5 kW, 50 Hz three-phase induction motor, the simulation shows a direct up under no load conditions. Simulation results of the overall system with a modulation index r = 0,8; C = 6 (elimination the 5^{th}, 7^{th}, 11^{th}, 13^{th} et 17^{th} order harmonics) and U_c = 100 V are given in Fig. 10a, b, c.

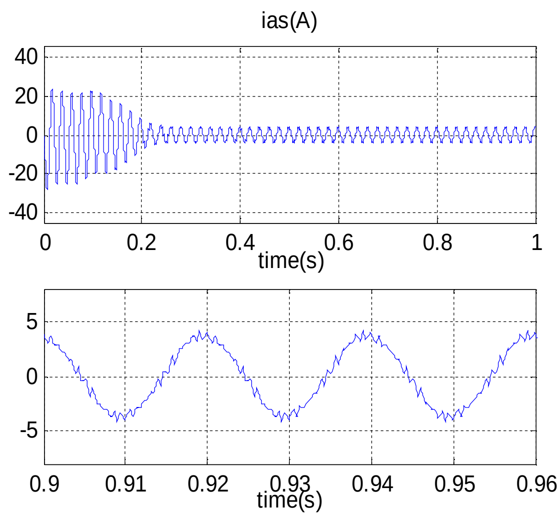
According to the Fig. 10c it noted that the form of the current is closely sinusoid and the influence of the harmonics of the high order harmonics than 17 and more is feeble and the torque is less disturbed.



(a) Speed



(b) Electromagnetic torque



(c) Phase current

Fig. 10: Dynamic behaviour of the induction machine supplied with the five level inverter.

6. Conclusion

In this paper, two algorithms for elimination in a five-level inverter has been proposed and evaluated. They are genetic algorithm and Newton-Raphson's methods.

The first method is a numerical method and the second is an evolutionary algorithm. The study shows the implementation of algorithm and its effectiveness to find solutions to this complex nonlinear optimization problem.

It has shown up; the nonlinear equation (10) doesn't have solution for any value of modulation index ***r*** and which the harmonic eliminated doesn't appear in the spectrum of the output line voltage.

The SHEPWM strategy made it possible to decrease the number of commutations per switch and to get a more sinusoidal stator current with fewer harmonics.

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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