

# HIGH PERFORMANCES OF FIVE-PHASE INDUCTION MACHINE FEEDING BY A $[3 \times 5]$ MATRIX CONVERTER

Mohamed Mounir Rezaoui\* — Lazhari Nezli\*\*  
— Mohand Oulhadj Mahmoudi\*\*

In this paper, we study an analytic technique to control matrix converter for a four-quadrant five-phase induction machine drive with use PWM five intervals modulation strategy. The multiphase induction machine is feeding by a matrix converter using a three-phase network. Special emphasis is given to the sinusoidal five phase voltage in the output and five phase voltage input current modulation. Simulation results are presented.

**Key words:** matrix converter  $[3 \times 5]$ , PWM three intervals modulation, five-phase induction machine, high performances

## 1 NOMENCLATURE

$U_R, U_S, U_T$	input voltages of matrix converter,
$V_A, V_B, V_C, V_D, V_E$	output voltages of matrix converter $[3 \times 5]$ ,
$i_s, i_r$	stator/rotor currents,
$i_{ds}, i_{qs}, i_{dr}, i_{qr}$	stator/rotor currents $d-q$ axis components,
$V_{ds}, V_{qs}, V_{dr}, V_{qr}$	stator/rotor voltages $d-q$ axis components,
$\phi_d, \phi_q$	stator flux $d-q$ axis components,
$R_r, R_s$	stator/rotor resistance,
$L_S, L_R$	stator/rotor inductance,
$L_m$	mutual inductance,
$L_d, L_q$	$d-q$ magnetizing inductance,
$T_{em}$	electromagnetic torque,
$T_r$	load torque,
$J$	total inertia,
$\omega_i, \omega_0$	input/output pulse
$P$	number of pole pairs,
$\Omega$	rotating speed,
$m, r$	modulation index, modulation rate,
$k$	index 1, 2, ... 5

## 2 INTRODUCTION

When a voltage source inverter is used to supply a machine, its stator higher harmonic current amplitudes are determined not only by the source amplitude and waveform, but also by the machine leakage inductances at particular frequencies. These inductances are a function of the number of phases and can be quite small so that certain harmonic currents have large amplitudes as mentioned by [1, 2, 3].

However, in the literature, studies have shown that the five-phases induction machine drive operates satisfactorily when fed from a pulse width modulation (PWM)

inverter [4, 5]. For this, and for our study we can see in the transport of electrical energy by three-phase systems in the past has led to the development of three-phases electromechanical converters. They have benefited from the rise of power switches. The performance of this conventional three-phase electrical machine associated with voltage inverters have thus been increased notably in the field of variable speed. This type of system is now widely available in standard industrial level [6]. However, the reduced number of phases can be a handicap in specific areas of applications. Thus, problems arise both in the inverter (which wants to replace them with matrix converter) that the machine when desired to increase the transmitted power without making changes on the network that feeds the system. Switches shall then indeed switch voltages and currents of higher amplitudes [6, 7].

The main objective of this study is to solve the problem of feeding a multiphase induction machine by a converter using the three-phase network. This make it possible firstly to enjoy the benefits of multiphase machines such as reducing the amplitude and increasing the frequency of torque pulsation, the reduction of harmonic currents rotor, by reducing the phase current without increasing the voltage per phase by lowering the harmonics of DC link current harmonics and higher reliability. By increasing the number of phases, it is also possible to increase the torque for a machine of the same volume and also benefit equally from the advantages of matrix converter such as the simplicity of the power circuit, the generation of the charging voltage amplitude and arbitrary frequency, the input currents and output sinusoidal shape and finally the functioning with a unity power factor for any load [5, 8, 9].

Current advances in power electronics and the development of computing processors can consider a finer control of these machines using PWM techniques [3]. Industrial applications, quoting the variable speed drives on board,

\* LAADI, Faculty of Science and Technology, University of Djelfa 17000 DZ, Algeria, mm.rezaoui@yahoo.fr; \*\* LCP, Ecole Nationale Polytechnique, 10 av. Pasteur, Hassen Badi, 16200, El Harrach, Algiers, Algeria, mo.mahmoudi@g.enp.edu.dz, lazhari.nezli@g.enp.edu.dz,

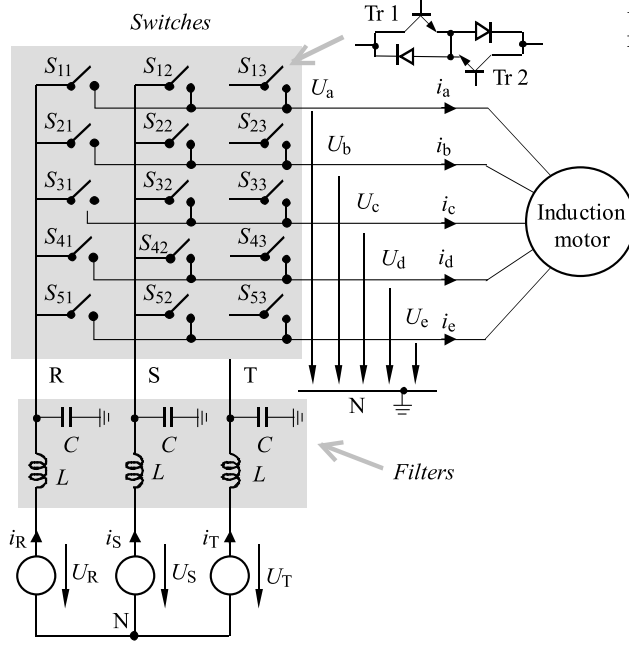


Fig. 1. Schematic diagram of the matrix converter

wind energy, active filter networks, ... [10, 11]. In the following we build a converter connected between the input phase which is everywhere and multiphase output (rectifier  $[3 \times 1]$ , filter  $[1 \times 1]$  and inverter  $[1 \times 5]$ ).

### 3 THE PROPOSED SYSTEM

Figure 1 illustrates the synoptic scheme of five-phase induction machine. Who was squirrel cage in rotor and dual stator, five phases winding shifted by  $2\pi/5$  electrical degrees, Iron saturation is neglected and the distribution of induction along the air gap is sinusoidal in the analysis.

Feed by a matrix converter which is controlled by PWM five intervals modulation strategy.

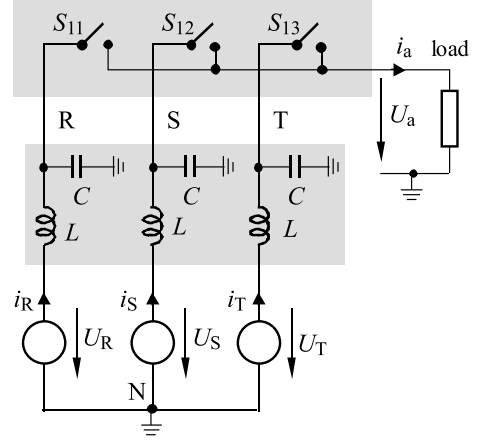


Fig. 2. The cellular commutation of matrix converter

Table 1. Matrix converter configuration

Configuration	The electrical quantity which characterizes
$E_1$	$U_a = U_R$
$E_2$	$U_a = U_S$
$E_3$	$U_a = U_T$

The equations of the phase voltages of the two windings, stator and rotor are written as follows

$$[V_s] = [R_s][I_s] + \frac{d[\phi_s]}{dt}, \quad (1)$$

$$[V_r] = [R_r][I_r] + \frac{d[\phi_r]}{dt}. \quad (2)$$

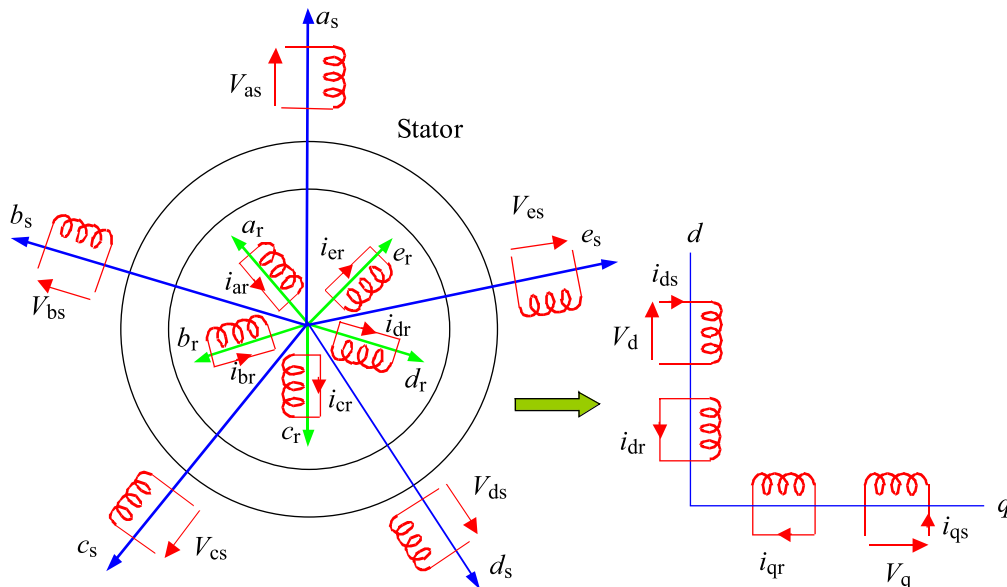


Fig. 3. The modeling of five-phases machine in the coordinates  $d$ - $q$

The electromagnetic torque is given by

$$T_{em} = \frac{p}{2} \left\{ [I_s]^\top \frac{d[L_{s,r}]}{d\theta} [I_r] \right\}. \quad (3)$$

The transformation of Park, transform a five-phases system (a, b, c, d and e) in a two-phase equivalent (d, q) rotating frame to obtain a simple mathematical model similar to the physical model of the system, this matrix can be written as follows [13–15]

$$P(\theta) = \sqrt{\frac{2}{5}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) & \cos(\theta - \frac{6\pi}{5}) & \cos(\theta - \frac{8\pi}{5}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{5}) & -\sin(\theta - \frac{4\pi}{5}) & -\sin(\theta - \frac{6\pi}{5}) & -\sin(\theta - \frac{8\pi}{5}) \end{bmatrix}. \quad (4)$$

By transforming the equations of stator voltages and the rotor voltages in the reference frame  $d$ - $q$  using the matrix of Park, and choosing the reference frame related to the rotating field to obtain the following system [16, 17]

$$\begin{aligned} V_{ds} &= R_s I_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs}, \\ V_{qs} &= R_s I_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds}, \\ 0 &= R_r I_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_s - \omega_r) \phi_{qr}, \\ 0 &= R_r I_{qr} + \frac{d\phi_{qr}}{dt} + (\omega_s - \omega_r) \phi_{ds}, \end{aligned} \quad (5)$$

with

$$\begin{aligned} \phi_{ds} &= L_s I_{ds} + L_m I_{dr}, \\ \phi_{qs} &= L_s I_{qs} + L_m I_{qr}, \\ \phi_{dr} &= L_s I_{dr} + L_m I_{ds}, \\ \phi_{qr} &= L_s I_{qr} + L_m I_{qs}. \end{aligned} \quad (6)$$

To complete the model we must add the mechanical equation of the electric torque provided by the machine and the mechanical equation of motion expressed as follows:

$$\begin{aligned} T_{em} &= \frac{L_m p}{L_r} (\phi_{dr} I_{qs} - \phi_{qr} I_{ds}), \\ T_{em} - T_r &= J \frac{d\Omega_r}{dt}. \end{aligned} \quad (7)$$

## 4 MODELING OF THE MATRIX CONVERTER

### 4.1 Structure of the matrix converter

The matrix converter is a static frequency and voltage converter, this is the main characteristic of conventional converters rectifier – inverter. It allows obtaining in output voltages a multiphase variable system: amplitude and frequency from an input multiphase's voltages of power supply network, as in [18, 19]. This converter topology is characterized by a matrix of twenty-five switches (matrix

$[3 \times 5]$ ), as the five phases of the network inputs are connected to the five phases of the converter output through bidirectional power switches (Fig. 1). The switch matrix converter can be modeled by two diodes and two transistors greatly reduce the number of possible configurations of the matrix converter, as in [18, 19]. Since the converter is an idealized coupling, the principle of causality leads to precise rules concerning the grouping of switches forming the converter, as in [16, 20]:

- Sources located on both sides of the group are necessarily different in nature.
- Continuity requires energy to retain, among the possible configurations of the operative part, that those who are physically possible: a non-zero voltage source can be short-circuited, a voltage source to zero can be set open circuit.

Finally, we deduce that for each cell one and only one switch should be closed, is reducing the number of possible configurations to  $3^5$ .

### 4.2 Cell work of a matrix converter

The commutations cellular present a symmetrical functional, and consequently a symmetrical control. The converter study is then reduced to the cellular commutation one (Fig. 3), [12, 18]. The commutation cellular has 3 possible configurations. Each of these configurations is characterized by a quantity shown in Table 1.

## 5 CONTROL STRATEGY OF MATRIX CONVERTER

The Principe control of the matrix converter is based on the analogy with the indirect converter with an intermediate circuit fictitious (rectifier/inverter) [19]. So to talk about the complexity of the matrix converter control, we adopt the advantage of the conventional converter by introducing a fictitious intermediate voltage, study them separately, rectifier – inverter. The fact that at any given time, it has at least one phase of the supply voltage which is positive and at least another phase is negative relative to neutral power in Fig. 4, one can choose fictitious potentials  $U^+$  and  $U^-$  like

$$U_d = U^+ - U^-, \quad (8)$$

where we call:  $U_d$  — the intermediate virtual potential,  $U_d^+$  — the virtual positive potential,  $U_d^-$  — the virtual negative potential.

The value of the virtual DC-voltage  $U_d$  will be varying as a function of line phase angle and the rectifier control functions. For example, in interval  $\pi/3 \leq \omega t \leq 2\pi/3$ , the phase the switches can be taken the values ( $R^+ = 1, S^+ = 0, T^+ = 0$ ) and ( $R^- = 0, S^- = 1, T^- = 0$ ).

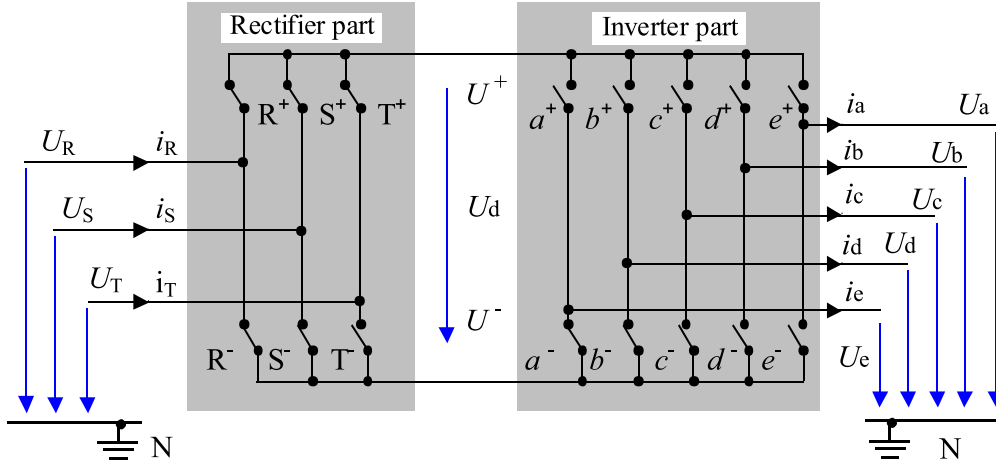


Fig. 4. Model of the matrix converter with middle fictitious circuit

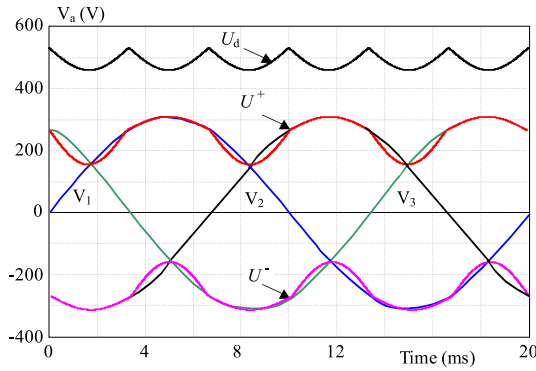
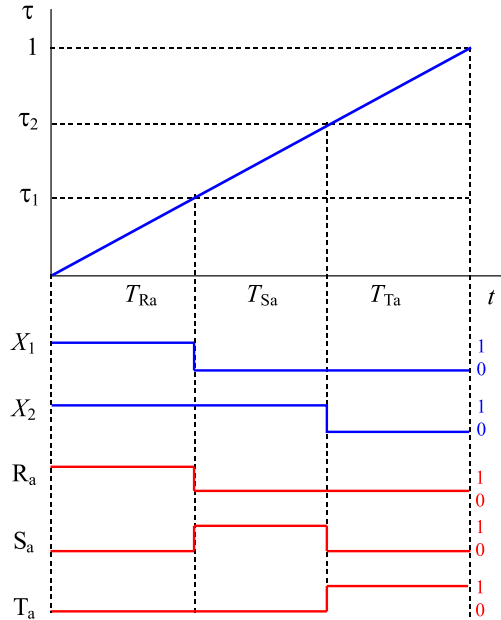
Fig. 5. The shape of the intermediate fictitious voltage  $U_d$ 

Fig. 6. PWM five intervals that control output phase

The potentials then are

$$U^+ = R^+ V_R + S^+ V_S + T^+ V_T$$

$$U^- = R^- V_R + S^- V_S + T^- V_T$$

### 5.1 Study of the rectifier part

In order to easily implement the rectifier, we define the matrix a function of rectifier as [17, 18]

$$\tau = \frac{\cos(\Phi - 2\pi/3)}{\cos \Phi} + 1 \quad (0 \leq \tau \leq 1) \quad (9)$$

with  $\Phi = (\omega t) \pmod{\pi/3} - \pi/6$ .

It allows the connection between the input voltages and the intermediate part fictitious as follows [19]

$$\begin{bmatrix} U^+ \\ U^- \end{bmatrix} = \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix} \begin{bmatrix} U_R \\ U_S \\ U_T \end{bmatrix}. \quad (10)$$

Considering the symmetry found in a recovery period, we may distinguish six intervals (Fig. 5).

### 5.2 Study of the inverter part

We will introduce the functions  $u_{cmk}$  modulations that can take continuous values between 0 and 1, to define the modulation matrix  $[M_0]$ . This allows a link between the middle potential and the output voltages of the matrix converter, as follows

$$\begin{bmatrix} U_a \\ U_b \\ U_c \\ U_d \\ U_e \end{bmatrix} = \begin{bmatrix} U_{cm1} & 1 - U_{cm1} \\ U_{cm2} & 1 - U_{cm2} \\ U_{cm3} & 1 - U_{cm3} \\ U_{cm4} & 1 - U_{cm4} \\ U_{cm5} & 1 - U_{cm5} \end{bmatrix} \begin{bmatrix} U^+ \\ U^- \end{bmatrix}. \quad (11)$$

Taking into account the two blocks rectifier – inverter, we obtain

$$\begin{bmatrix} U_a \\ U_b \\ U_c \\ U_d \\ U_e \end{bmatrix} = \underbrace{\begin{bmatrix} U_{cm1} & 1 - U_{cm1} \\ U_{cm2} & 1 - U_{cm2} \\ U_{cm3} & 1 - U_{cm3} \\ U_{cm4} & 1 - U_{cm4} \\ U_{cm5} & 1 - U_{cm5} \end{bmatrix}}_{M(t)} \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix} \begin{bmatrix} U_R \\ U_S \\ U_T \end{bmatrix}. \quad (12)$$

### 5.3 Modulation fictitious middle voltage

The output reference voltage phases are defined as follows

$$U_{\text{ref}_k} = U_m \sin(\omega_0 t - 2\pi(k-1)/5) \quad (13)$$

with  $\omega_0 = 2\pi f_0$  and  $k = 1, 2, 3, 4$  and  $5$ .

Determining the functions of waves (standard reference functions) consist to modulate the fictitious middle voltage given above

$$U_{cmk} = r \cos \Phi \sin(\omega_0 t - 2\pi(k-1)/5) + 1/2 \quad (14)$$

### 5.4 Three intervals PWM modulation

The PWM is a well established technique for converters with pulse. We see for that, the control of matrix converter each output phase must be switched at each input phase during a specified range of the period pulse. We must therefore divide the pulse period into three intervals (number of output phases). For this, in fact use a technique similar to that of conventional PWM modulators [14, 15, 17]. The saw tooth signal reference will be compared to a control signal. In this way, we obtain in the output a binary signal by phase, indicating the state of power switch. The figure below shows the time sequence of the switches of a cell over a period of pulsation in Fig. 6. PWM strategy is characterized by two parameters, the modulation index  $m$  and the rate of modulation  $r$ .

The equation of the carrier is defined as follows

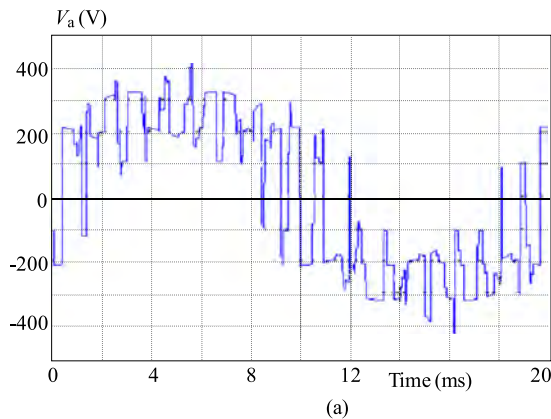
$$U_p = t/T_p, \quad 0 \leq t \leq T_p. \quad (15)$$

The output binary signals  $X_i$  of PWM modulator are defined as [18]

$$X_i = \begin{cases} 1 & \text{if } \tau_{xi} > U_p, \\ 0 & \text{if } \tau_{xi} \leq U_p. \end{cases} \quad (16)$$

The control signals of switches of the matrix converter are obtained using a simple logic as

$$\begin{aligned} T_{a-R} &= X_1, \\ T_{b-R} &= \overline{X_1} \& X_2, \\ T_{c-R} &= \overline{X_2} \& X_3, \end{aligned} \quad (17)$$



Taking into account the previous equations we define the reference signals  $\tau_X$

$$\begin{aligned} \tau_{X1k} &= R^+ U_{cmk} + R^-(1 - U_{cmk}), \\ \tau_{X2k} &= \tau_{X1k} + S^+ U_{cmk} + S^-(1 - U_{cmk}). \end{aligned} \quad (18)$$

Conversion Function of  $V_a, V_b, V_c, V_d$  and  $V_e$  are given in terms of  $U_a, U_b, U_c, U_d$  and  $U_e$  as

$$\begin{aligned} V_a &= (2U_a - U_b - U_c - U_d - U_e)/5, \\ V_b &= (2U_b - U_a - U_c - U_d - U_e)/5, \\ V_c &= (2U_c - U_a - U_b - U_d - U_e)/5, \\ V_d &= (2U_d - U_a - U_b - U_c - U_e)/5, \\ V_e &= (2U_e - U_a - U_b - U_c - U_d)/5. \end{aligned} \quad (19)$$

## 6 SIMULATION AND RESULTS

To verify the performance of the modulation technique applied to five intervals to control the matrix converter, a Matlab simulation environment was conducted. From the results presented in Figures 7 and 8, we find that

- 1 The response time of the speed is very fast,
- 2 In steady state, the frequency of the electromagnetic torque is equal to the frequency of the voltage  $V_a$  given by the  $[3 \times 5]$  matrix converter.
- 3 The induction machine can support clearly the nominal load.
- 4 The current absorbed by the machine is almost sinusoidal.

## 7 CONCLUSION

This paper presents the performance of a PWM converter matrix  $[3 \times 5]$  feeding an induction machine 5-phase. This matrix structure is obtained by association between two converters:

- Converter  $[3 \times 3]$ , which consists of a main rectifier  $[3 \times 1]$ , a filter  $[1 \times 1]$  and an inverter  $[1 \times 3]$ .

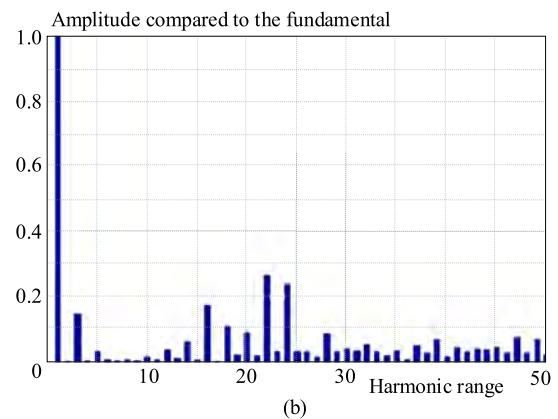
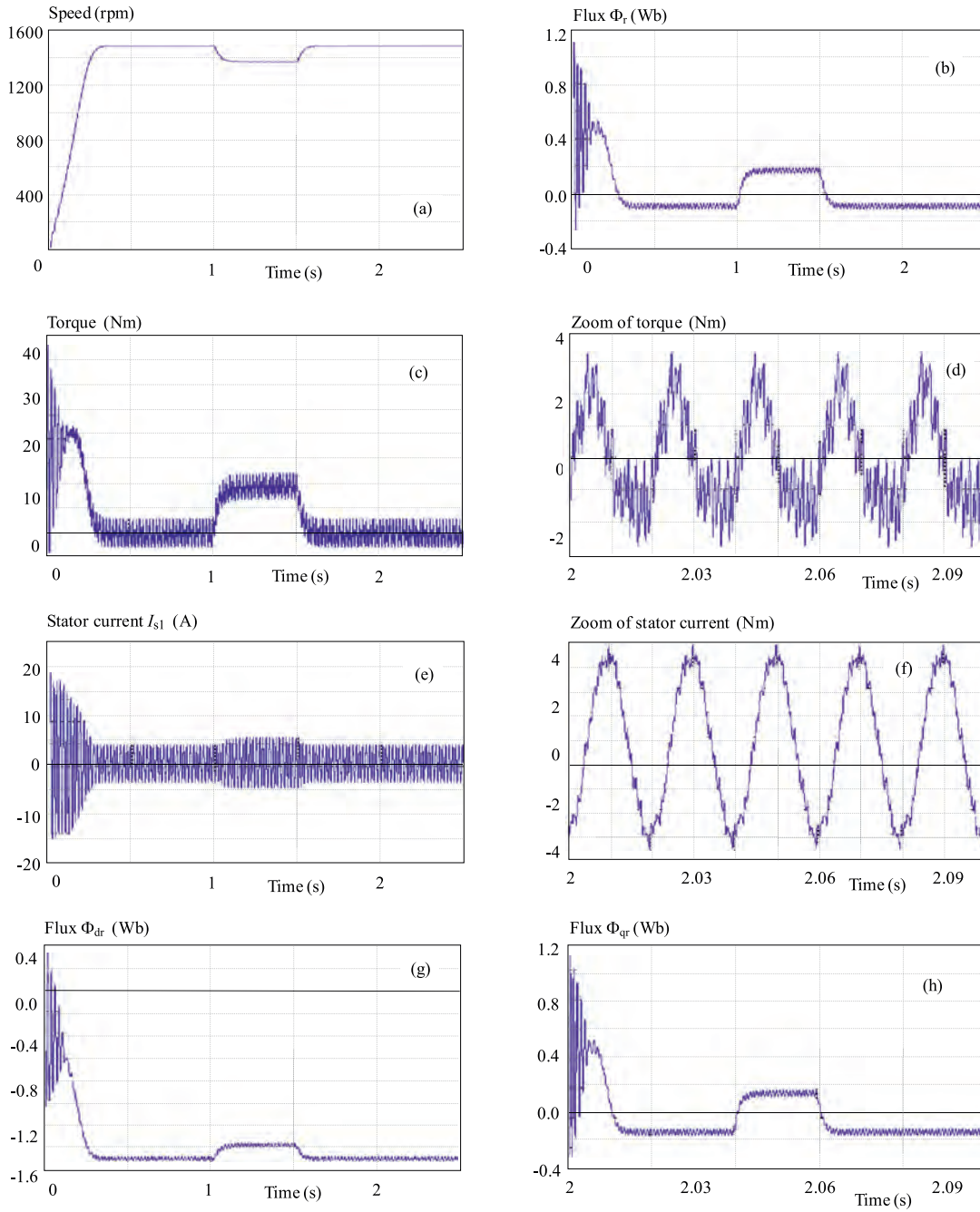


Fig. 7. The output voltage and her harmonic spectrum ( $f_0 = 50$  Hz,  $m = 21$ ,  $r = 0.8$ )



**Fig. 8.** Performances of the matrix converter – five-phase induction machine association with five intervals, PWM strategy ( $f_0 = 50$  Hz,  $m = 21$ ,  $r = 0.8$ ). Application of rated load between  $t = 1$  and  $1.5$  s

- Converter  $[5 \times 5]$ , which consists of a main rectifier  $[5 \times 1]$ , a filter  $[1 \times 1]$  and an inverter  $[1 \times 5]$ .

In the industrial case, the network is available for three phase and polyphase machine control (five phases in our case), it is interesting to use this matrix structure which is direct connection between the network and the three-phase machine. In addition, the study uses a new modulation technique ever used in the literature to control the matrix converter modulation strategy *ie* three intervals appropriate to converter  $[3 \times 5]$ .

The results obtained show that the output voltage of the matrix converter has a sinusoidal form with a coeffi-

cient of harmonic distortion (THD) of the stator current less than 30 %. The behavior of the machine with the matrix converter gave better results both in the static than dynamic regime.

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**Mohamed Mounir Rezaoui** was born in 1981, received the Engineer diploma and Magister degree in Electrical Engineering from National Polytechnic School ENP, algiers, Algeria, in 2005 and 2007, respectively. Where he is currently working toward the Ph.D. degree in control of polyphase matrix converter. From 2009 to 2010, he was with the Nucleare Research centre as a Senior Researcher in departement of robotic and teleoperation systems in CRNB, Birine Algeria. In December 2010, he joined the Ziane Achor University of Djelfa, Algeria. His areas of research interest are in Power Electronics, Electrical Machines Drive and Matrix converter.

**Lazhari Nezli** was born in Algeria in 1957. He received the electrical engineering degree, the Magister degree and the doctorate degree from the national polytechnic school of Algiers (Algeria) in 1982, 1986 and 2006 respectively. Since 1987, he holds teaching and research positions at the department of electrical engineering ENP, where he is currently full professor. His areas of research interest are Modeling and electrical machines drives.

**Mohand Oulhadj Mahmoudi** was born in Algiers (Algeria) in 1956. He received the Engineer diploma, the Magister degree and the doctorate degree in Electrical Engineering from the National Polytechnic School of Algiers (Algeria) in 1982, 1986 and 1999 respectively. Since 1986, he holds teaching and research position at the electrical engineering department where he is currently professor. His areas of research interest are in Power Electronics and Electrical Machines Drive.



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