A COMPARATIVE PERFORMANCE STUDY BETWEEN A MATRIX CONVERTER AND A THREE-LEVEL INVERTER FED INDUCTION MOTOR

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SUMMARY

In spite of the use of multi-level inverters for industrial high power applications, there has been considerable interest in the potential benefits of matrix converter technology, especially where size and long-term reliability are important factors.

This paper is proposing a comparative study between a three-phase matrix converter ensuring an AC/AC conversion and a standard three-level voltage source inverter. The Study is proposed in order to show for the same performance, the merits and the advantages of the matrix converter with respect to the three-level inverter.

A complete performance study of each converter feeding both a passive R-L load as well as an induction motor is being carried out and performance results are being obtained.

The work is accomplished by means of the "Matlab®/Simulink®" software. This last one makes it possible to simulate the dynamic systems in a simple way and in a graphical environment.

Keywords: *matrix converter, three-level inverter, bidirectional switches, induction motor*

1. INDRODUCTION

Currently, the majority of the electrical drives are three-phase AC current. These drives operate with variable speed where the traction constitutes a good example. The use of these drives requires variable speed and variable voltage high power converters. The interest is oriented towards multi-level converters (three-, five-, seven-level and more) [1]. But increasing interest is also oriented towards the potential benefits of new categories of AC/AC converter (the matrix converter) [2], especially for high power applications where size, weight, and long-term reliability are important factors.

In this paper, the authors propose a complete comparative study between a three-phase three-level voltage inverter and a three-phase matrix converter when first feeding a passive R-L load and then a three phase induction motor.

2. THE MATRIX CONVERTER

The basic matrix converter circuit [3], [4] can be that represented by figure 2.1.

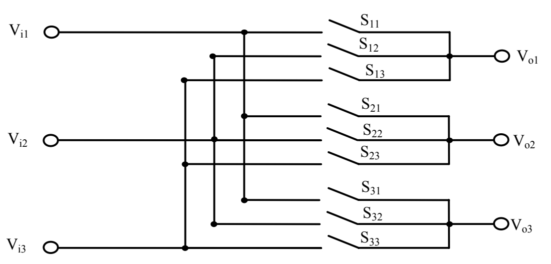

Fig. 2.1 Basic matrix converter circuit

The symbol S_{ij} represents the ideal bidirectional switches, where V_o represents the output voltage and V_i represents the input voltage. Let $[V_i]$ be the vector of the input voltages given as:

$$\left[V_i\right] = V_{im}\begin{bmatrix}\cos(\omega_i t)\\ \cos(\omega_i t + 2\pi/3)\\ \cos(\omega_i t + 4\pi/3)\end{bmatrix} \quad (2.1)$$

And $[V_o]$ the vector of the desired output voltages given as:

$$\left[V_o\right] = V_{om}\begin{bmatrix}\cos(\omega_o t)\\ \cos(\omega_o t + 2\pi/3)\\ \cos(\omega_o t + 4\pi/3)\end{bmatrix} \quad (2.2)$$

The problem consists now in finding a matrix M known as the modulation matrix, such that

$$[V_o] = [\mathrm{M}].\,[V_i] \quad (2.3)$$

and

$$[\mathrm{I}_i] = [M]^{\mathrm{T}}\,.\,[I_o] \quad (2.4)$$

where $[M]^{\mathrm{T}}$ represents the transposed matrix of $[M]$.

The development of equation (2.3) gives:

$$\begin{bmatrix}V_{o1}\\ V_{o2}\\ V_{o3}\end{bmatrix} = \begin{bmatrix}m_{11} & m_{12} & m_{13}\\ m_{21} & m_{22} & m_{23}\\ m_{31} & m_{32} & m_{33}\end{bmatrix}\begin{bmatrix}V_{i1}\\ V_{i2}\\ V_{i3}\end{bmatrix} \quad (2.5)$$

where m_{ij} are the coefficients of modulation.

During commutation, the bidirectional switches must operate according to the following rules:

- At every instant t, only one switch S_{ij} ($i = 1,2,3$) is ON in order to avoid short-circuit between the phases.

- At every instant t, at least two switches S_{ij} (j=1,2,3) *are ON* to ensure a closed loop load current.
- The switching frequency $f_s = \omega_s / 2\pi$ must have a value eight times higher than the maximum of (f_i, f_o), ($f_s >> 8.\max(f_i, f_o)$).
- The sum of the conduction times used to synthesize the same output phase, must be equal to Ts known as the sequential period which is equal to $1/f_s$.

The time t_{ij} known as the modulation time; is defined as:

$$t_{ij} = m_{ij}.T_s \tag{2.6}$$

The following solutions for m are proposed by Venturini [5], [6]:

$$m_{11} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i)] + \alpha_2' \cos[-(\omega_o - \omega_i)]$$

$$m_{12} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 2\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i) - 2\pi/3]$$

$$m_{13} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 4\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i) - 4\pi/3]$$

$$m_{21} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 4\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i) - 2\pi/3]$$

$$m_{22} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i)] + \alpha_2' \cos[-(\omega_o + \omega_i) - 4\pi/3]$$

$$m_{23} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 2\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i)]$$

$$m_{31} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 2\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i) - 4\pi/3]$$

$$m_{32} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i) - 4\pi/3] + \alpha_2' \cos[-(\omega_o + \omega_i)]$$

$$m_{33} = 1/3 + \alpha_1' \cos[(\omega_o - \omega_i)] + \alpha_2' \cos[-(\omega_o + \omega_i) - 2\pi/3]$$

where $\alpha_1' = \alpha_2' = \dfrac{V_{i1}}{3V_{o1}}$

The average value of the voltage of the first output phase during the $K^{\acute{e}me}$ sequence is:

$$v_{i1}^{(k)} = m_{11}^{(k)} v_{i1}^{(k)} + m_{12}^{(k)} v_{i2}^{(k)} + m_{13}^{(k)} v_{i3}^{(k)} \tag{2.7}$$

that is,

$$v_{i1}^{(k)} = \frac{1}{T_s}\left[t_{11}^{(k)} v_{i1}^{(k)} + t_{12}^{(k)} v_{i2}^{(k)} + t_{13}^{(k)} v_{i3}^{(k)}\right] \tag{2.8}$$

with

$$T_s = t_{11} + t_{12} + t_{13} \tag{2.9}$$

The synthesis of the first output phase will be done according to the following equation (2.10):

$$\begin{cases} v_{i1} & 0 \le t-(k-1)T_S < m_{11}^{(k)} T_s \\ v_{i2} & (m_{11}^{(k)})T_S \le t-(k-1)T_S < (m_{11}^{(k)} + m_{12}^{(k)})T_S \\ v_{i3} & (m_{11}^{(k)} + m_{12}^{(k)})T_S \le t-(k-1)T_S < (m_{11}^{(k)} + m_{12}^{(k)} + m_{13}^{(k)})T_S \end{cases} \tag{2.10}$$

3. THE THREE-LEVEL INVERTER

3.1. Structure of the three-level inverter

The schematic representation of the three-level inverter [7], [8] as shown in Fig. 3.1 is composed of three arms and two d.c voltage sources. Each inverter arm consists of four pairs of diode-bidirectional switch and two median diodes allowing having zero level of the output voltage of the inverter. The centre point of each arm is connected to a d.c source.

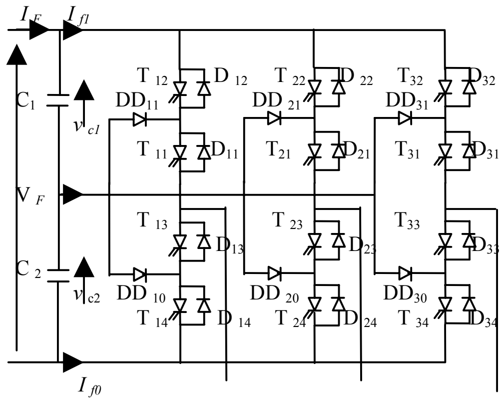

Fig. 3.1 Three-level inverter structure

3.2. Inverter arm complementary control

The structure symmetry of the three-level inverter allows the arm modelling as shown in figure 3.2. One initially defines the global model of an arm, and then deduces that of the complete inverter.

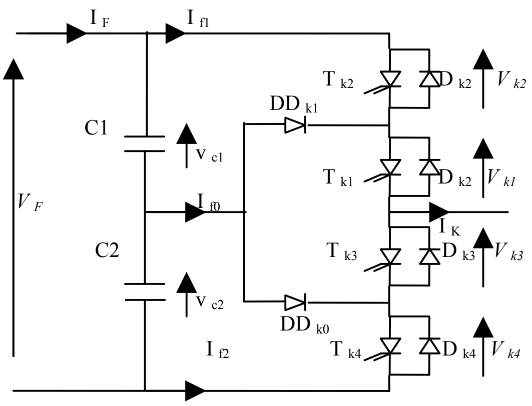

Fig. 3.2 Structure of an of inverter arm

To avoid short-circuits of the voltage sources by conduction, and in order to deliver the three-level of the desired voltages, then one must make the inverter work in its commendable mode. A static converter commendable mode means that the transitions between its various configurations depend only on its external and not internal control.

Three complementary controls can be applied to the three-level inverter arm as follows:

$$\begin{cases} G_{K3} = \overline{G}_{K1} \\ G_{K4} = \overline{G}_{K2} \end{cases}; \quad \begin{cases} G_{K2} = \overline{G}_{K1} \\ G_{K4} = \overline{G}_{K3} \end{cases}; \quad \begin{cases} G_{K4} = \overline{G}_{K1} \\ G_{K3} = \overline{G}_{K2} \end{cases}$$

G_{k1}	G_{k2}	G_{k3}	G_{k4}	V_{ko}
0	0	1	1	V_{C2}
0	1	0	1	unknown
1	0	1	0	0
1	1	0	0	V_{C1}

Tab. 3.1 The switches excitation

with G_{KS} the trigger control of the Tks switch of the arm K.

In order to have the total commendable mode of the three-level inverter, one must eliminate the case which gives an unknown answer.

By translating this complementary control using the connection functions of the switches of arm K, one finds:

$$\begin{cases} F_{k1} = 1 - F_{k4} \\ F_{k2} = 1 - F_{k3} \end{cases} \tag{3.1}$$

One defines the connection function of the half-arms noted as F_{km}^{b} with:

$$m = \begin{cases} 1 & \text{for the higher half-arm composed of } TD_{k1} \text{ and } TD_{k2} \\ 0 & \text{for the lower half-arm composed of } TD_{k3} \text{ and } TD_{k4} \end{cases}$$

The connection functions of the half-arms are expressed by means of the connection functions of the switches as follows:

$$\begin{cases} F_{k1}^{b} = F_{k1} F_{k2} \\ F_{k0}^{b} = F_{k3} F_{k4} \end{cases} \tag{3.2}$$

The nodal potentials a,b,c of the three-phase three-level inverter compared to the medium point, are given by the following equations system:

$$\begin{cases} v_{ao} = F_{11} F_{12} v_{c1} - F_{13} F_{14} v_{c2} \\ v_{bo} = F_{21} F_{22} v_{c1} - F_{23} F_{24} v_{c2} \\ v_{co} = F_{31} F_{32} v_{c1} - F_{33} F_{34} v_{c2} \end{cases} \tag{3.3}$$

By introducing the connection functions of the half-arms, one will obtain:

$$\begin{cases} v_{ao} = F_{11}^{b} v_{c1} - F_{10}^{b} v_{c2} \\ v_{bo} = F_{21}^{b} v_{c1} - F_{20}^{b} v_{c2} \\ v_{co} = F_{31}^{b} v_{c1} - F_{30}^{b} v_{c2} \end{cases} \tag{3.4}$$

The inverter output phase voltages are deduced in terms of the nodal potentials compared to the medium point by the following relation:

$$\begin{cases} v_a = \frac{1}{3}\left(2v_{ao} - v_{bo} - v_{co}\right) \\ v_b = \frac{1}{3}\left(-v_{ao} + 2v_{bo} - v_{co}\right) \\ v_c = \frac{1}{3}\left(-v_{ao} - v_{bo} + 2v_{co}\right) \end{cases} \tag{3.5}$$

From the relation (3.4) and (3.5), one obtains the matrix system linking the functions of the inverter half-arms to the phase voltages at the load terminals given as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{11}^{b} \\ F_{21}^{b} \\ F_{31}^{b} \end{bmatrix} v_{c1} - \begin{bmatrix} F_{10}^{b} \\ F_{20}^{b} \\ F_{30}^{b} \end{bmatrix} v_{c2} \right\} \tag{3.6}$$

In the case where $v_{c1} = v_{c2} = \frac{V_f}{2}$, the relation (3.5) is reduced to

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} F_{11}^{b} - F_{10}^{b} \\ F_{21}^{b} - F_{20}^{b} \\ F_{31}^{b} - F_{30}^{b} \end{bmatrix} \frac{V_f}{2} \tag{3.7}$$

The three-level inverter control strategy used in this work is based on the sinusoidal PWM technique.

4. SIMULATION RESULTS

The three-level inverter and the matrix converter described above were simulated for three different desired output frequencies (*f_o = 25 Hz, 50 Hz and 100 Hz*), with a switching frequency f_s = 5KHz. Both converters are first feeding a passive R-L load (*Rs=20Ω and Lr=0.04H*) and then a *50HP, 460V* induction motor driving a *200 N.m* resistive torque.

Fig. 4.1 and Fig. 4.2 show the output voltages for both converters, while Fig. 4.3 and Fig. 4.4 show the passive R-L load as an illustrative example where one can see clearly the impact of the output frequency variation on the R-L load current. The results are almost the same for both converters.

Fig. 4.5 and Fig. 4.6 show the induction motor performance when fed from both converters. These figures show clearly that the current, speed and torque characteristics are normal and almost similar for both the three-level inverter and the matrix converter.

4.1. The three-level inverter output voltage

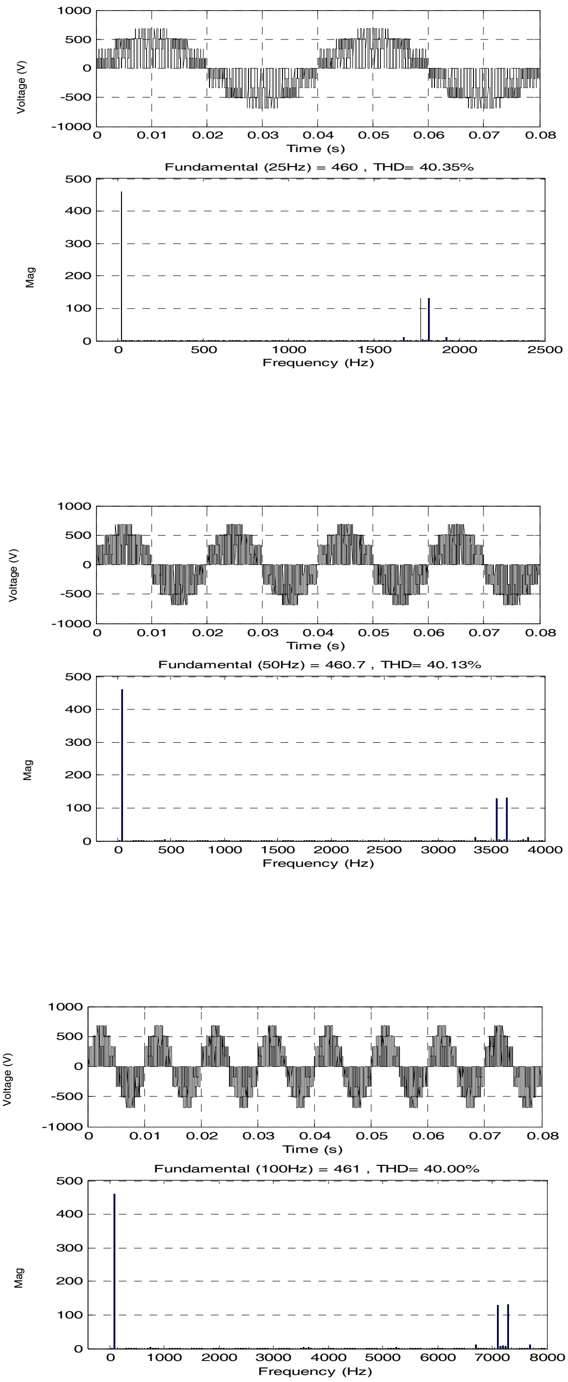

Fig. 4.1 Three-level inverter output voltage and its spectrum for f_o = 25 Hz, 50 Hz and 100 Hz

4.2. The matrix converter output voltage

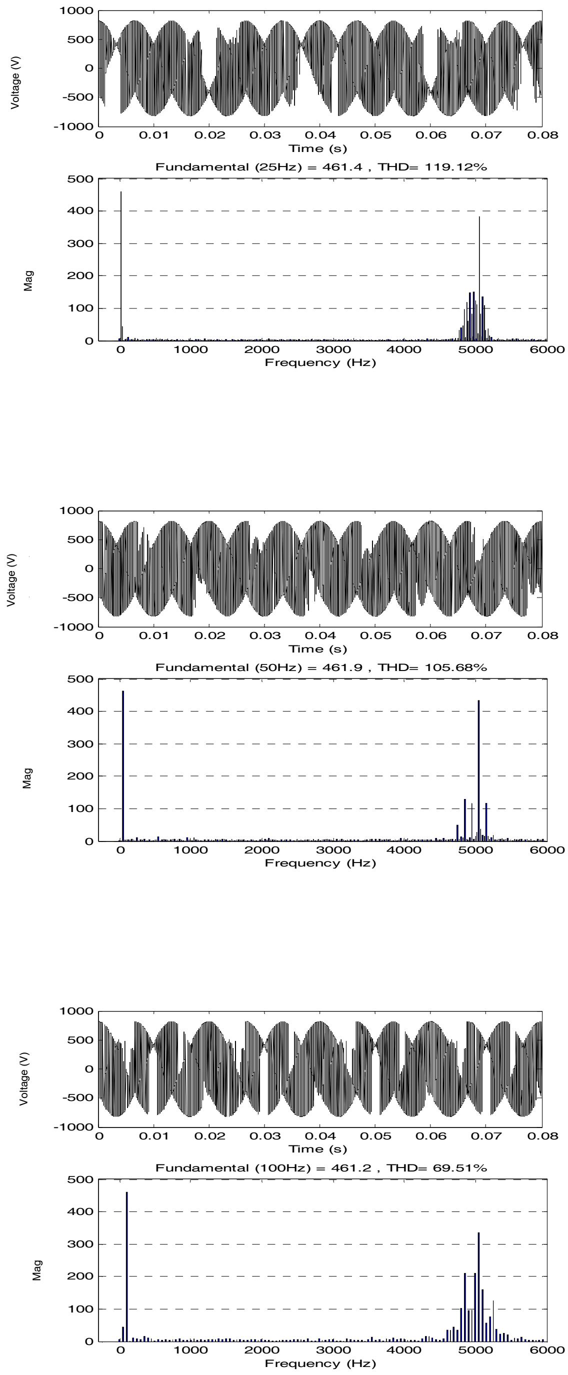

Fig. 4.2 Matrix converter output voltage and its spectrum for f_o = 25 Hz, 50 Hz and 100 Hz

4.3. The three-level inverter R-L load current

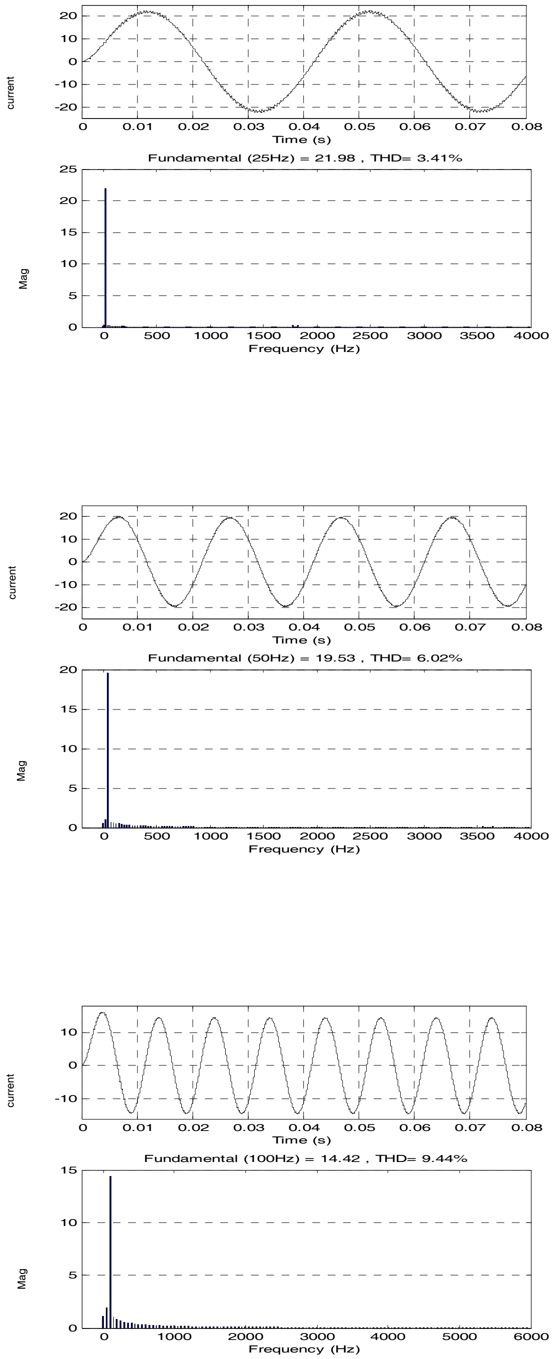

Fig. 4.3 Three-level inverter R-L load current and its spectrum for $f_o = 25$ Hz, 50 Hz and 100 Hz

4.4. The matrix converter R-L load current

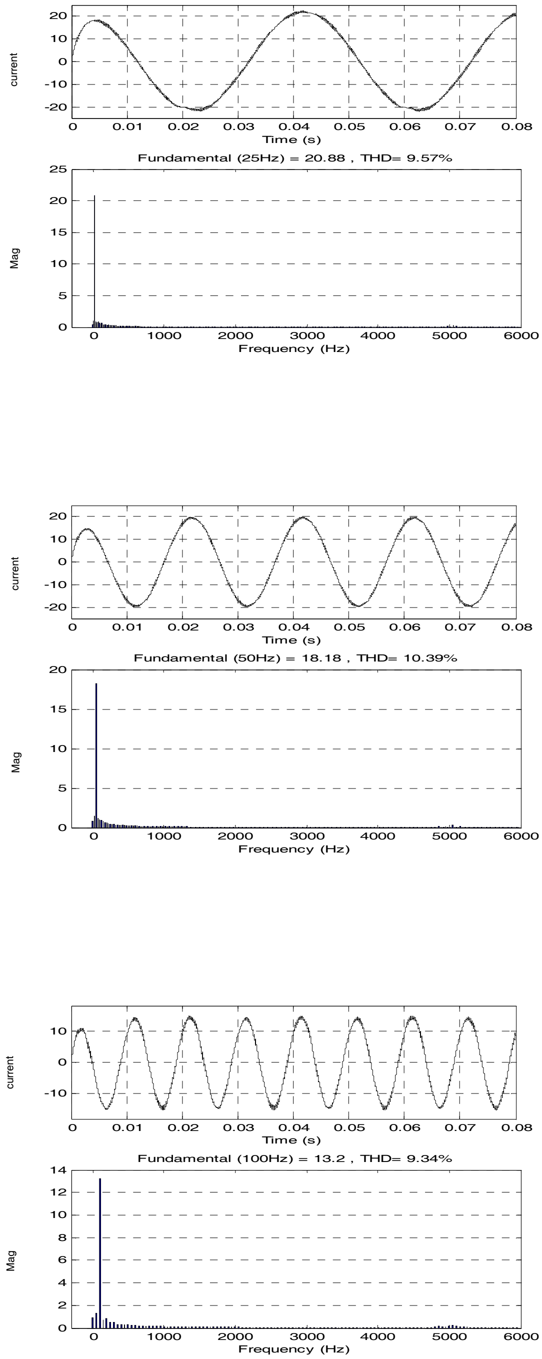

Fig. 4.4 Matrix converter R-L load current and its spectrum for $f_o = 25$ Hz, 50 Hz and 100 Hz

4.5. The three-level inverter fed induction motor performance for f_o=50Hz

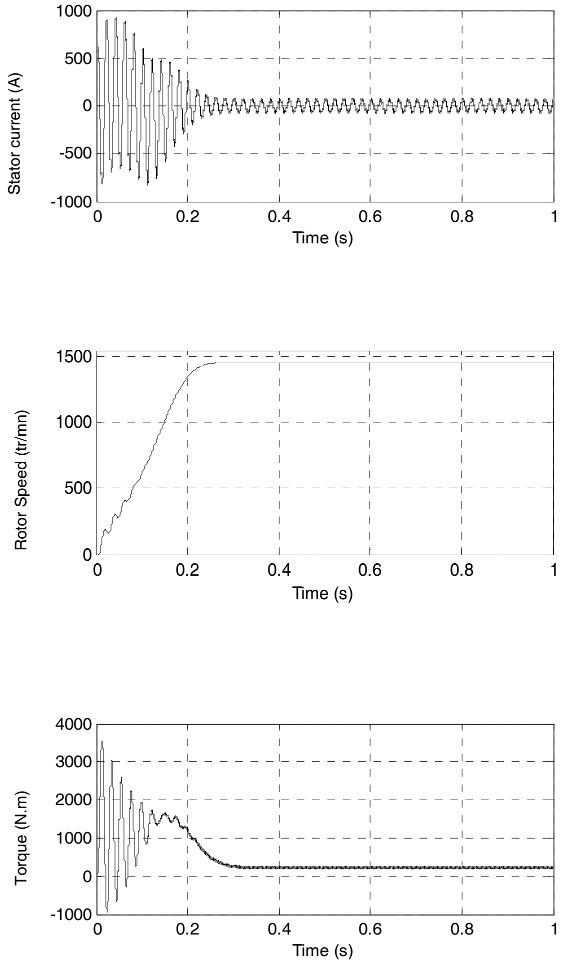

Fig. 4.5 Stator current, rotor speed, and torque of a three-level inverter fed induction motor

4.6. The matrix converter fed induction motor performance for f_o=50Hz

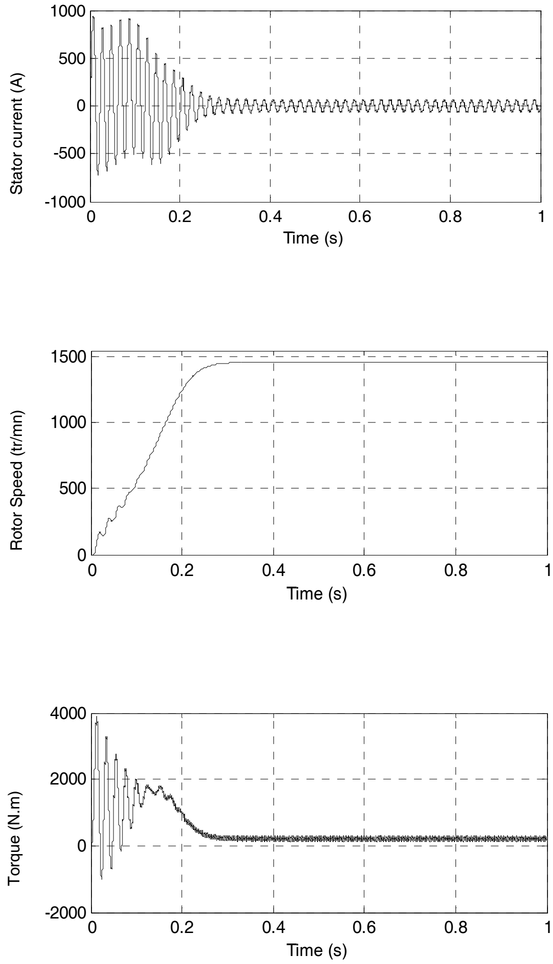

Fig. 4.6 Stator current, rotor speed, and torque for a matrix converter fed induction motor

4.7. Matlab/Simulink diagrams and blocks

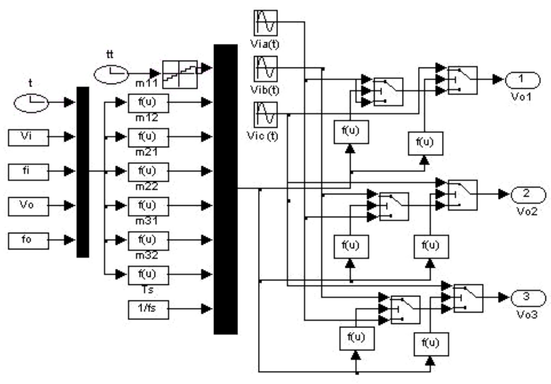

Fig. 4.7.1 The matrix converter simulink®/Matlab diagram

In this section are presented both the converters functional diagrams as well as the R-L passive load and induction motor functional diagrams used for the simulation work.

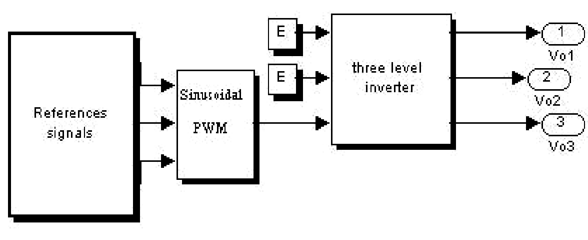

Fig. 4.7.2 The 3-level inverter simulink®/Matlab diagram

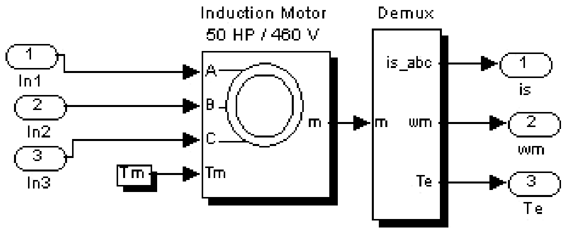

Fig. 4.7.3 Block Simulink® of the induction motor

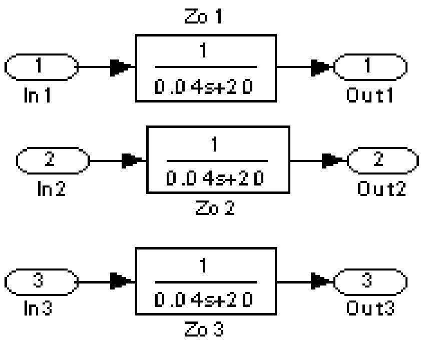

Fig. 4.7.4 Block Simulink® of the passive R-L load

5. CONCLUSION

The performance results obtained from both matrix converter and three-level inverter are shown to be almost similar, either for the passive R-L load case or the induction motor case. From this fact, one can conclude that the matrix converters can easily replace the three-level inverter in all industrial applications.

The merits of the matrix converter become more tangible and more visible in comparison to the multi-level inverter particularly for high power, high voltage applications. The matrix converter allows a direct synthesizing of the desired voltage and therefore presents a technical-economic advantage due to the elimination of the intermediate stage and the output filter used in three-level inverters. Another advantage for the matrix converter is that the number of switches reduces from 30 components (12 bidirectional inverter switches, 6 blocking diodes and 12 rectifier diodes) in the three-level inverter to nine components only in the matrix converter resulting in a less complicated system.

ACKNOWLEGMENTS

In memory to our best colleague Dr T. Korti who was the first one to have introduced the matrix converters in our electrical department at the University USTO of Oran, Algeria.

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BIOGRAPHIES

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