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Control of Matrix Converter Fed Induction Motor Drive

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Abstract: This paper presents a variable speed control of the squirrel induction machine fed by a three-phase matrix converter. Principle of vector control for induction motor and vector control strategy in synchronous reference frame are described. The use of matrix converter allows the availability of better switching devices, bi-directional power flow and sinusoidal input and output waveform. Also, the advantages of matrix converter are combined with the advantages of the field oriented control technique where Venturini algorithm is applied. We study the operation of the motor in the four regions of speed-torque plane. At this effect, the simulation results of the whole system are carried out with four quadrants of motor operations and the performance results obtained are presented and analyzed. A good performance of induction motor fed by a matrix converter is proved.

Keywords: Matrix converter; induction motor; vector control; modelling; simulation.

1. Introduction

In the recent decades, an increasing attention has been drawn to the AC/AC matrix converters due to its advantages as: higher power density, smaller size converter and easier maintenance compared to AC/DC/AC converter, it provides bidirectional power flow, sinusoidal input/output currents without harmonics compared to commercial inverters and adjustable input power factor [1, 2]. In addition, it allows to control: the rotor currents magnitude, frequency and input power factor[3-5]. Thus, matrix converter (MC) allows a compact design due to the lack of dc-link capacitors for energy storage [2]. However, most existing models generally used a conventional vector control [6, 7]. The conventional proportional integral controller (PI) is widely used in the control of d-q rotor currents because of its simple structures and good performances. The use of matrix converter presents also a several disadvantages such as: limited availability of the bidirectional power electronic devices working at high frequencies, complex control. The maximum ratio between output and the input voltage is 86,6% and a high cost of the systems protection for the bidirectional switches [4, 8, 9].Despite all these disadvantages, matrix converters have been used in several areas [10-15].The simulation of a voltage control for a three-phase to three-phases matrix converter working in different regions of operations have been studied in [9].The present work is articulates on the modeling, control, simulation and analysis of squirrel induction motor (IM) fed by matrix converter.

This paper is structured as follow: the second section describe the vector model of squirrel induction motor. The modeling and Venturini algorithm control of the induction motor are described in the third section. After, the chain composed of matrix converter, induction motor and the Venturini algorithm are programmed under Matlab/Simulink environment and the analysis of the performances in different regions of operations are given in the fourth section. Finally, a conclusion on the realized parts is presented.

2. Modelling of Matrix Converter

As shown in Fig. 1, the matrix converter is constituted of nine bi-directional switches, arranged as three sets of three where the input phases are connected to the three output lines. The switches are controlled in such a way that the average output voltages and currents are sinusoids of the required frequency and magnitude [16, 17].



Figure1.Schematic block diagram of matrix converter induction motor drive

A single stage matrix converter is used to convert nine AC phase input voltage into three AC phase output, with a control of magnitude and frequency current output. So, matrix converter can generate unlimited output frequency compared to those of input. The switching functions are defined as follows [18]:

$$S_{jk} = \begin{cases} 1 \rightarrow S_{jk} \text{closed} \\ 0 \rightarrow S_{jk} \text{open} \end{cases}$$
(1)

With, $i \in \{A, B, C\}$ and $k \in \{a, b, c\}$.

The three phase output voltages V_a , V_b , V_c can be synthesized in terms of input voltages V_A , V_B , V_C and switching functions S_{jk} by the following equation [19, 20]:

$$\begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_{A} \\ V_{B} \\ V_{C} \end{bmatrix}$$
(2)

The input currents i_A , i_B , i_C can be also calculated in terms of output currents i_a , i_b , i_c as:

$$\begin{bmatrix} i_{A} \\ i_{B} \\ i_{C} \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} i_{a} \\ i_{b} \\ i_{c} \end{bmatrix}$$
(3)

Consequently, from the equations (2) and (3), the output line currents and input line voltages are presented by equations (4) and (5) as follow:

$$\begin{bmatrix} \mathbf{i}_{AB} \\ \mathbf{i}_{BC} \\ \mathbf{i}_{CA} \end{bmatrix} = \begin{bmatrix} \mathbf{s}_{Ab} & \mathbf{s}_{Ac} & \mathbf{s}_{Aa} \\ \mathbf{s}_{Bb} & \mathbf{s}_{Bc} & \mathbf{s}_{Ba} \\ \mathbf{s}_{Cb} & \mathbf{s}_{Cc} & \mathbf{s}_{Ca} \end{bmatrix} \begin{bmatrix} \mathbf{i}_{ab} \\ \mathbf{i}_{bc} \\ \mathbf{i}_{ca} \end{bmatrix}_{(4)}$$
$$\begin{bmatrix} \mathbf{V}_{ab} \\ \mathbf{V}_{bc} \\ \mathbf{V}_{ca} \end{bmatrix} = \begin{bmatrix} \mathbf{s}_{Ab} & \mathbf{s}_{Bb} & \mathbf{s}_{Cb} \\ \mathbf{s}_{Ac} & \mathbf{s}_{Bc} & \mathbf{s}_{Cc} \\ \mathbf{s}_{Aa} & \mathbf{s}_{Ba} & \mathbf{s}_{Ca} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{AB} \\ \mathbf{V}_{BC} \\ \mathbf{V}_{CA} \end{bmatrix}_{(5)}$$

Where, the modulations functions for output line are given as:

$$S_{Aa} = \frac{1}{3}(S_{Ac} - S_{Aa}) - \frac{1}{3}(S_{Bc} - S_{Ba})_{S_{Ab}} = \frac{1}{3}(S_{Aa} - S_{Ab}) - \frac{1}{3(S_{Ba} - S_{Bb})}S_{Ac} = \frac{1}{3}(S_{Ab} - S_{Ac}) - \frac{1}{3}(S_{Bb} - S_{Bc})$$

$$S_{Ba} = \frac{1}{3}(S_{Bc} - S_{Ba}) - \frac{1}{3}(S_{Cc} - S_{Ca})_{S_{Bb}} = \frac{1}{3}(S_{Ba} - S_{Bb}) - \frac{1}{3}(S_{Ca} - S_{Cb})_{S_{Bc}} = \frac{1}{3}(S_{Bb} - S_{Bc}) - \frac{1}{3}(S_{Cb} - S_{Cc})$$

$$S_{Ca} = \frac{1}{3}(S_{Cc} - S_{Ca}) - \frac{1}{3}(S_{Ac} - S_{Aa})_{S_{Cb}} = \frac{1}{3}(S_{Ca} - S_{Cb}) - \frac{1}{3}(S_{Aa} - S_{Ab})_{S_{Cc}} = \frac{1}{3}(S_{Cb} - S_{Cc}) - \frac{1}{3}(S_{Ab} - S_{Ac})$$

3. Venturini Matrix Converter Algorithm

Generally, two (2) constraints on the matrix converter control are considered: in the aim to prevent short-circuit between input terminals, any two input terminals should never be connected to the same output line and eliminate open circuit to the output terminals. The switching constraint is defined as follow:

$$\sum S_{ja} = \sum S_{jb} = \sum S_{jc} = 1$$
(6)

Venturini algorithm or the direct transfer function approach is used to control only 27 switching among 512 possible combinations[21]. Furthermore, it allows generating variable-frequency and variable amplitude sinusoidal output voltages. The calculation time of each output phase voltage t_{jk} is a fraction of the switching frequency period T_{s} .

$$\mathbf{t_{jk}} = \mathbf{S_{jk}} \cdot \mathbf{T_{s}}_{(7)}$$

With:

$$\sum t_{ja} = \sum t_{jb} = \sum t_{jc} = T_{s}$$
(8)

The maximum ratio between output and the input voltage is denoted by q_{s} which represent the maximum ration, equal to 86, 6% [4].

The three-phase sinusoidal input voltages can be calculated by the following equation:

$$[V_{j}(t)] = V_{is} \begin{bmatrix} \cos(\omega_{i}t) \\ \cos\left(\omega_{i}t + \frac{2\pi}{3}\right) \\ \cos\left(\omega_{i}t + \frac{4\pi}{3}\right) \end{bmatrix}_{(9)}$$

Furthermore, V_{is} and Θ_i is given in function of the measured V_{BC} and V_{AB} in the following form [22]:

$$V_{is}^{2} = (4/9) (V_{AB}^{2} + V_{BC}^{2} + V_{AB}.V_{BC})_{(10)}$$

$$\theta_{i} = \arctan\left(\frac{V_{BC}}{\sqrt{3}\left(\frac{2}{3}V_{AB} + \frac{1}{3}V_{BC}\right)}\right)_{(11)}$$

So, we can write V_{os} and Θ_o as :

$$V_{os} = (2/3) (V_a^2 + V_b^2 + V_c^2)_{(12)}$$
$$\theta_o = \arctan\left(\frac{V_b - V_c}{\sqrt{3}V_a}\right)_{(13)}$$

The voltage gainis calculated as:

$$q = \sqrt{\frac{V_{os}^2}{V_{is}^2}}_{(14)}$$

The matrix transfer for output phases can be calculated according to the following equations:

$$S_j k = \frac{1}{3} [1 + 2(V_j V_k) / (V_i S^2) + \frac{2}{3} \frac{q}{q_s} \sin(\omega_i t + \phi_j) \cdot \sin(3\omega_i t) (15)$$

So, j = {A, B, C}, k = {a, b, c}, $\phi_j = 0, \frac{2\pi}{3}, \frac{4\pi}{3}$.

The structure of the simulation block diagram that we have developed for the simulation of the control of the matrix converter is represented by Figure 2:



Figure2.Subsystem control of MC

4. Modeling of the Induction Motor

The induction motor (IM) model is presented and controlled in synchronous d-q reference frame where the d-axis is aligned with the stator flux linkage vector. It is controlled by acting on the direct and quadrature components of the rotor voltage. In effect, it enables the decoupled control between the electrical torque and the rotor excitation current is obtained.. Furthermore, the electromagnetic torque and the stator reactive power can be controlled by means of the rotor currents i_{rq} and i_{rd} , respectively.

The mathematical model of the induction motor expressed in a d-q synchronously rotating reference frame, are presented as follow [23]:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A} \cdot \mathbf{X} + \mathbf{B} \cdot \mathbf{U} \\ \mathbf{Y} = \mathbf{C} \cdot \mathbf{X} \quad (16) \end{cases}$$

Where, the state vectors *X*, *Y* and *U* are respectively:

$$X = Y = \begin{bmatrix} i_{sd} \ i_{sq} \ i_{rd} i_{rq} \end{bmatrix}^{T} and U = \begin{bmatrix} V_{sd} V_{sq} \ V_{rd} \ V_{rq} \end{bmatrix}^{T}.$$

$$A = \begin{bmatrix} -a_{1} & aw + w_{s} & a_{3} & a_{5}w \\ -aw - w_{s} & -a_{1} & -a_{5}w & a_{3} \\ a_{4} & -a_{6}w & -a_{2} & -\frac{w}{\sigma} + w_{s} \\ a_{6}w & a_{4} & \frac{w}{\sigma} - w_{s} & -a_{2} \end{bmatrix}_{(17)}^{(17)}$$

$$B = \begin{bmatrix} b_{1} & 0 & -b_{3} & 0 \\ -aw - w_{s} & -a_{1} & -a_{5}w & a_{3} \\ -b_{3} & 0 & b_{2} & 0 \\ 0 & -b_{3} & 0 & b_{2} \end{bmatrix}_{(18)}^{(18)}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{(19)}^{(19)}$$

$$With: a = \frac{1 - \sigma}{\sigma}; a_{1} = \frac{R_{s}}{\sigma_{L_{s}}}; a_{2} = \frac{R_{r}}{\sigma_{L_{r}}}; a_{3} = \frac{R_{r}M}{\sigma_{L_{s}L_{r}}}; a_{4} = \frac{R_{s}M}{\sigma_{L_{s}L_{r}}}; a_{5} = \frac{M}{\sigma_{L_{s}}};$$

$$a_{6} = \frac{M}{\sigma_{L_{r}}}; b_{1} = \frac{1}{\sigma_{L_{s}}}; b_{2} = \frac{1}{\sigma_{L_{r}}}; b_{3} = \frac{M}{\sigma_{L_{s}L_{r}}}; \sigma = 1 - \frac{M^{2}}{\sigma_{L_{s}L_{r}}};$$

The stator and rotor flux as a function of currents are given as:

[φ _{so}]	=	۲Ls	0	Lo	0]	[I _{sq}]	
φ_{sd}		0	Ls	0	Lo	Isd	
φ_{rq}		L	0	L_r	0	i _{rg}	
[\\\Phi_rd]		Lõ	Lo	0	L _r	i _{rd}	(20)

With, $L_s = L_{ls} + L_o and L_r = L_{lr} + L_o$.

Moreover, R_s and R_r denote the stator and rotor resistance, respectively. L_s is the stator and L_r the rotor self-inductances, where the quantities L_{ls} and L_{lr} are the stator and rotor leakage inductances, respectively, and L_o denote the magnetizing inductance.

The mechanical equations of the system can be characterized by [24]:

$$J\frac{d\Omega}{dt} = T_{em} - T_{l} - f\Omega_{(21)}$$

Where, the electromagnetic torque is give as follows:
$$T_{em} = p \cdot \frac{M}{L_{s}} \left[\left(\varphi_{sq} i \right]_{rd} - \varphi_{sd} i_{rq} \right)_{(22)}$$

With, *p*: number of poles pairs; *M*: mutual inductance; *J*: moment of inertia; T_{em} : electromagnetic torque; T_{l} : load torque.

5. Vector Control

In order to realize the control low, the induction machine model is presented in synchronous d-q reference frame where the d-axis is aligned with the rotor flux linkage vector.



Figure 3. Orientation of the d-q frame

We obtain:

$$\begin{cases} \varphi_{rq} = 0\\ \varphi_{rd} = \varphi_{r} (23) \end{cases}$$

So, we deduce:

$$\begin{cases} i_{rq} = -\frac{M_{sr}}{L_r} i_{sq} \\ i_{sq} = -\frac{L_r}{M_{sr}} i_{rq} \end{cases}$$
(24)

However, one can establish the relationship between φ_{eq} and i_{rq} as well as between T_{em} and i_{rq} . These relations are given by the expressions (25) and (26), respectively:

$$\varphi_{sq} = -\sigma \frac{L_s L_r}{M_{sr}} i_{qr} \quad (25)$$

 $T_{em} = pM_{sr}(i_{qs}i_{dr} - i_{ds}i_{qr}) = -p\phi_{dr}i_{qr} (26)$

Simulation Results and Interpretations

In order to analyze the functioning of the conversion structure considered in the four quadrant of speedtorque plane as shown in Table 1.

Table 1. Four-region operation of the drive system						
Speed	Torque	quadrant	Operating regime			
> 0	>0	Ι	Motor			
> 0	< 0	II	Generator			
< 0	< 0	III	Motor			
< 0	>0	IV	Generator			

Figure 4 display the electromagnetic torque and the rotor speed variations of the process, for a reference speed ensuring a starting and an inversion of rotation, simultaneously. As can be seen from this figure, the

possible operation regions delimiting the four quadrants are indicated. The motor parameters are given in Table 2.

Table 2. Simulation parameters of IM					
Symbol	Designation	values			
R_s	Stator resistance	4.85 Ω			
R_r	Rotor resistance	3.805 Ω			
L_s	Stator inductance	0.274H			
L_r	Rotor inductance	0.274H			
L_m	Mutual inductance	0.258H			
р	Pole pairs	2			
J	Moment of inertia	0.0031 Kg/m^2			
f	Friction coefficient	0.001136N.m.s/rad			
V_s	Stator voltage	600v			

Note that for the first time interval after a start at zero time, the speed increases and stabilizes at the reference speed 80rd/s after a duration of 0.5s and after the inversion of 80rd/s to -80rd/s at the instant 1 second, the inversion time lasts0.5s. Thereafter, at the instant t=2 seconds, we took new set points for lower speeds (50rd / s) and (-50rd / s). We remark that the two (2) sizes (speed and torque) follow their references correctly.



Figure 4. Speed and Electromagnetic torque

Figure 5 and 6, show the output and input voltages of the matrix converter, respectively. We particularly notice that the simulation waveforms of the output voltages approximate sinusoidal forms.



Figure 5. Matrix output voltages



Figure 6. Matrix converter input voltages

Otherwise, the Figure 7 illustrates the superimposition of the three quantities, in particular, t output voltage of the matrix converter, its input voltage and the phase current "a" of the induction motor (With a scale of 10 times).

Finally, through the figure 8, we have shown the evolution of the motor speed as a function of the electric torque in the four possible operation quadrants of the drive system. This corresponds to the two imposed references speeds.



Figure 7.Waveforms for input voltage, output current and motor current for 80rd/s



Figure 8.Different operating modes

6. Conclusion

In this paper, a detailed modeling of matrix converter, induction motor and a field oriented controller taking into account the four quadrants operation is proposed. The developed models are validated by numerical simulation under Matlab/Simulink software to investigate the validity of the study. It has been clearly shown that this system can operated in the four quadrants of motor operations. Hence, this structure is highly recommended for industrial installations require variable speed operation.

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