SCALAR CONTROL FOR A MATRIX CONVERTER

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ABSTRACT

The authors compare two control strategies for direct AC-AC matrix converters; namely the Venturini method and the scalar strategy control method. The performance comparison of the two strategies is made under unbalanced distorted torque, rotor speed and stator current operation.

The simulation of the three-phase matrix converter feeding an induction motor was accomplished by means of the "Matlab®/Simulink®" software. This package makes it possible to simulate the dynamic systems in a simple way and in graphic environment.

Keywords: *matrix converter, Venturini method, Scalar control strategy, coefficients of modulation, induction motor.*

1. INTRODUCTION

The performances of an induction motor drive fed by a conventional inverter are similar to those of a matrix converter but the main advantages of the last one are:

- Elimination of the intermediate stage (rectifier, DC-link capacitor)
- Bi-directional power flow capability
- Sinusoidal input/output current and adjustable input power factor.

Furthermore, because of a high integration capability and higher reliability of the semiconductor structures, the matrix converter topology is recommended for extreme temperatures and critical volume/weight applications. Various techniques of modulation have been developed to be applied to the matrix converter control [1,4]. Some of these techniques make use of the scalar approach (Venturini and Roy), others are based on the vector approach such as the direct and indirect space vector modulation (SVM and ISVM) [7,8].

The aim of this paper is to present a detailed comparative study between the two different scalar approaches namely, Venturini and Roy, when applied to the control of an induction motor. The study deals with the motor '(current, speed and torque) performance response with respect to both techniques. This will enable us to identify the merits of each of them in order to make a judicious choice for their use in matrix converter control applications.

2. THEORY OF THE MATRIX CONVERTER

The basic diagram of a matrix converter can be that represented by Fig. 1.

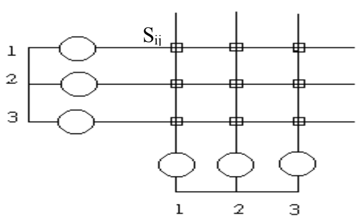

Fig. 1 Basic circuit of a matrix converter

The symbol S_{ij} represents the ideal bidirectional switches, where i represents the index of the output voltage and j represents the index of the input voltage.

Let $[V_i]$ be the vector of the input voltages given as:

$$[V_i] = V_{im} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + 2\pi/3) \\ \cos(\omega_i t + 4\pi/3) \end{bmatrix} \tag{1}$$

and the vector $[V_o]$ of the desired output voltages.

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

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

$$[V_o] = [M].\,[V_i] \tag{3}$$

and

$$[I] = [M]^{T}.\,[I] \tag{4}$$

$[M]^T$ represents the transposed matrix of $[M]$.

The development of the equation (3) gives:

$$\begin{bmatrix} V_{o1} \\ V_{o2} \\ V_{o3} \end{bmatrix} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} V_{i1} \\ V_{i2} \\ V_{i3} \end{bmatrix} \tag{5}$$

where m_{ij} are the modulation coefficients.

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

- At every instant t, only one switch S_{ij} (i = 1,2,3) works in order to avoid short-circuit between the phase.
- At every instant t, at least two switches S_{ij} (j = 1,2,3) works to ensure a closed loop load current.
- The switching frequency $f_s=\omega_s/2\pi$ must have a value twenty times higher to the maximum of f_i,f_o ($f_s >>> 20max\,(f_i,f_o)$).
- During the period T_s known as sequential period which is equal to $1/f_s$, the sum of the time of conduction being used to synthesize the same output phase, must be equal to T_s.

Now a time t_{ij} ; called time of modulation, can be defined as:

$$t_{ij}= m_{ij}.T_S \tag{6}$$

3. VENTURINI METHOD

For a set of three-phase input voltages with constant amplitude and frequency $f_i = \omega_i/2\pi$, this method calculates the duty cycle of each of the nine bidirectional switches. The result when implemented allows the generation of a set of three-phase output voltages by sequential piecewise sampling of the input waveforms.

The three phase output voltage thus obtained should desirably track a predefined reference waveform and when a three phase load is connected, the input currents of magnitude I_i and angular frequency ω_i should be in-phase with the input voltages.

To attain the above features, a mathematical approach is employed. The relationship between the input and output voltages and that of the output and input currents are written respectively as:

$$\begin{bmatrix} V_{o1}(t) \\ V_{o2}(t) \\ V_{o3}(t) \end{bmatrix} = \begin{bmatrix} m_{11}(t) & m_{12}(t) & m_{13}(t) \\ m_{21}(t) & m_{22}(t) & m_{23}(t) \\ m_{31}(t) & m_{32}(t) & m_{33}(t) \end{bmatrix} \begin{bmatrix} V_{i1}(t) \\ V_{i2}(t) \\ V_{i3}(t) \end{bmatrix} \tag{7}$$

where m_{ij}(t) $(i,j=1,2,3)$ represents the duty cycles of a switch connecting output phase i to input phase j within one switching sample interval.

At any time t, $0\leq m_{ij}(t) \leq 1$ and

$$\sum_{j=1}^{3} m_{ij}(t) = 1 \qquad (i = 1,2,3) \tag{8}$$

To obtain maximum output to input voltage ratio, a reference three phase voltage is defined as

$$\begin{bmatrix} V_{o1}(t) \\ V_{o2}(t) \\ V_{o3}(t) \end{bmatrix} = V_{om} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t - 2\pi/3) \\ \cos(\omega_o t) - 4\pi/3 \end{bmatrix} - \frac{V_{om}}{6} \begin{bmatrix} \cos(3\omega_o t) \\ \cos(3\omega_o t) \\ \cos(3\omega_o t) \end{bmatrix} + \frac{V_{im}}{4} \begin{bmatrix} \cos(3\omega_i t) \\ \cos(3\omega_i t) \\ \cos(3\omega_i t) \end{bmatrix} \tag{9}$$

where V_{om} and V_{im} are the magnitudes of output and input fundamental voltages, respectively, and ω_o and ω_i correspond, to the output and input angular frequencies. When $V_{om} \leq (\sqrt{3}/2)V_{im}$ the functional solutions for the duty cycles $m_{ij}(t)$ can be determined and the general formula is given as:

$$\begin{aligned} m_{ij} = \frac{1}{3}\Bigg\{ & 1 + 2Q\cos(\omega_i t - 2(j-1)\frac{\pi}{3})\Bigg[\cos(\omega_o t - 2(i-1)\frac{\pi}{3}) \\ & - \frac{1}{6}\cos(3\omega_o t) + \frac{1}{2\sqrt{3}}\cos(3\omega_i t)\Bigg] \\ & - \frac{2Q}{3\sqrt{3}}\Bigg[\cos(4\omega_i t - 2(j-1)\frac{\pi}{3}) \\ & - \cos(2\omega_i t - 2(1-j)\frac{\pi}{3}\Bigg\}\Bigg] \end{aligned} \tag{10}$$

where i, j = 1,2,3 and $Q = V_{om}/V_{im}$.

Commutation of $m_{ij}(t)$ is carried out at a sample frequency f_s wich also defines the converter switching frequency[1], [2], [3].

4. THE SCALAR CONTROL STRATEGY

As stated in [4], a straightforward approach to generate the active and zero states of matrix switches in Fig. 1 consists of using the instantaneous voltage ratio of specific input phase voltages. Let us define the following phase voltages present at input port:

$$\begin{cases} V_A = V_{im}\cos(\omega_i t) \\ V_B = V_{im}\cos(\omega_i t - \frac{2\pi}{3}) \\ V_C = V_{im}\cos(\omega_i t - \frac{4\pi}{3}) \end{cases} \tag{11}$$

At the output port of the converter, the value of any instantaneous output phase voltage may be expressed by the eq12, where K-L-M are variable subscripts, any of which may be assigned A, B or C according to the rules below.

$$v_o = \frac{1}{T_s}[t_K v_K + t_L v_L + t_M v_M] \tag{12}$$

$$t_K + t_L + t_M = T_s \tag{13}$$

Rule 1: At any instant, the input phase voltage which has a polarity different from both others is assigned to "M".

Rule 2: The two input phase voltages which share the same polarity, are assigned to K and L, the smallest one of the two, in absolute value, being "K". Then t_K and t_L are chosen such that:

$$\frac{t_K}{t_L} = \frac{v_K}{v_L} = \rho_{KL} \tag{14}$$

for the interval where:

$$0 \le \frac{v_K}{v_L} \le 1 \tag{15}$$

Expressions given in eq12 and 13 are similar to that ones originally proposed by [1]. Eq14 defines the active time ratio between two out of the three switches, in one commutating leg of the output port (see Fig. 1); this time ratio (t_K/t_L) is proportional to the instantaneous voltage ratio (v_K/v_L) of their associated input phases. The ratio must be established with the smaller instantaneous voltage divided by the larger one, as stated in eq15.

The converter switching pattern depends only on the SCALAR comparison of input phase voltages and the instantaneous value (v_o) of the desired output voltage. The following gives the proper procedure to obtain the respective values of t_K, t_L and t_M during one period T_s of the sequence (or the carrier) frequency f_s.

For a specific interval where $0 \le v_K / v_L \le 1$, the instantaneous phase voltage ratio ρ_{KL} is:

$$\rho_{KL} = \frac{v_K}{v_L} \tag{16}$$

And the active times for three switches associated with the desired output voltage v_o become:

$$t_L = \frac{T_s(v_o - v_M)}{\rho_{KL}v_K + v_L - (1+\rho_{KL})v_M} \tag{17}$$

$$t_K = \rho_{KL} t_L \tag{18}$$

$$t_M = T_s - (1 + \rho_{KL})t_L \tag{19}$$

Using again the current value of ρ_K . Eq17 can be further developed such as:

$$t_L = \frac{T_s(v_o - v_M)v_L}{[v_K^2 + v_L^2 + v_M^2 - (v_K + v_L + v_M)v_M]} \tag{20}$$

In a balanced three phase system, the summation of the three instantaneous phase voltage is zero. So the following relationships can be obtained:

$$\frac{t_L}{T_s} = \frac{(v_o - v_M)v_L}{v_K^2 + v_L^2 + v_M^2} = \frac{(v_o - v_M)v_L}{1{,}5v_i^2} \tag{21}$$

$$\frac{t_K}{T_s} = \frac{(v_o - v_M)v_K}{1{,}5v_i^2} \tag{22}$$

$$\frac{t_M}{T_s} = 1 - \frac{t_K + t_L}{T_s} \tag{23}$$

The duty cycle of commutators K and L is proportional to the instantaneous value of the corresponding input phase voltage v_K and v_L multiplied by the voltage difference between the desired output voltage v_o and the input phase voltage v_M **.** It should be noted at this point that the output voltage v_o , (i.e v_a, v_b, v_c), can be any kind of waveform, including DC values...

Solving Eq21, 22 and 23 for a given voltage ratio. $V_{om}/V_{im} = Q \le 0.5$, will yield positive value for times t_k, t_L and t_M as in the case of Venturini control algorithm.

For a higher voltage transfer ratio, some negative time values start to appear because of the instantaneous voltage limitation at the input port of the DFC. However, modulation techniques proposed by Maytum [6] work well with the scalar strategy.

Hence, by modifying the switching times of the basic scalar control law, it is possible to add both the supply neutral point modulation at $3\omega_i$ and the load neutral point modulation at $3\omega_o$ to obtain an overall voltage transfer ratio of $Q = \sqrt{3}/2$. Eq20 is then modified by changing the term v_o by the following expression:

$$v_o' = v_o + \frac{1}{4}v_i\cos(3\omega_i t) - \frac{1}{6}v_o\cos(3\omega_o t) \tag{24}$$

5. SIMULATIONS RESULTS

Simulation was carried out, by keeping fixed the supply voltage of the induction motor (the output of the matrix converter) and varying only the frequency f_o in order to be able to compare the motor performance for both strategies presented above.

The matrix converter described above is simulated for three different desired output frequencies (*fo = 25 Hz*, *50 Hz and 100 Hz*), with a switching frequency *fs* = 5KHz. Both converters are first feeding a *50HP, 460V* induction motor driving a *200 N.m* resistive torque.

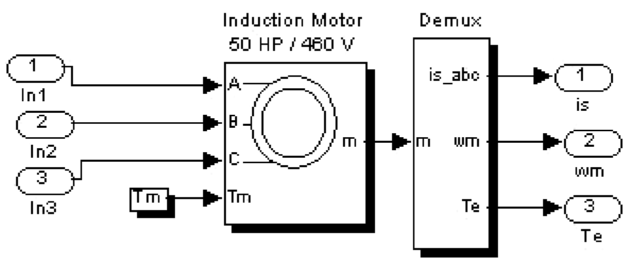

Fig. 2 Block Simulink® of the induction motor

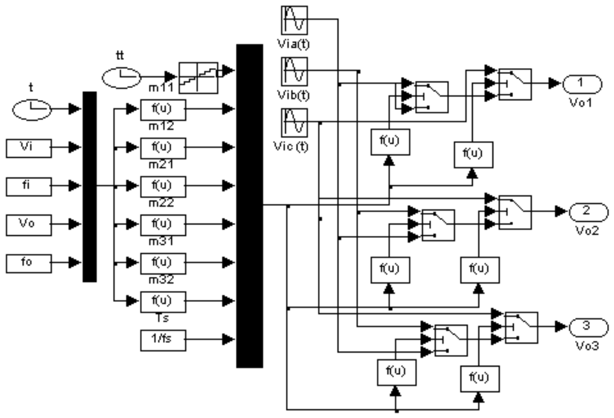

Fig. 3 The matrix converter simulink®/Matlab diagram (Venturini method)

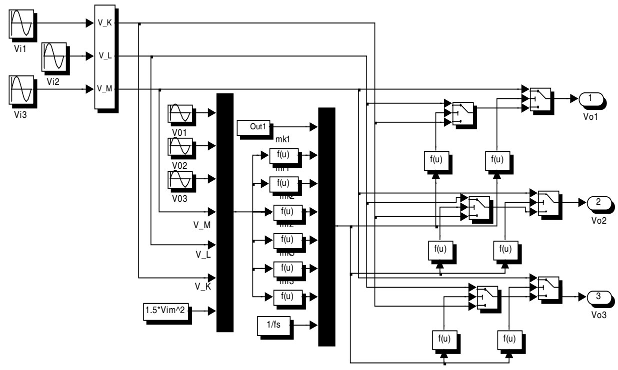

Fig. 5 The matrix converter simulink®/Matlab diagram (Scalar strategy control)

5.1. Results of Venturini method (f_o = 25 Hz)

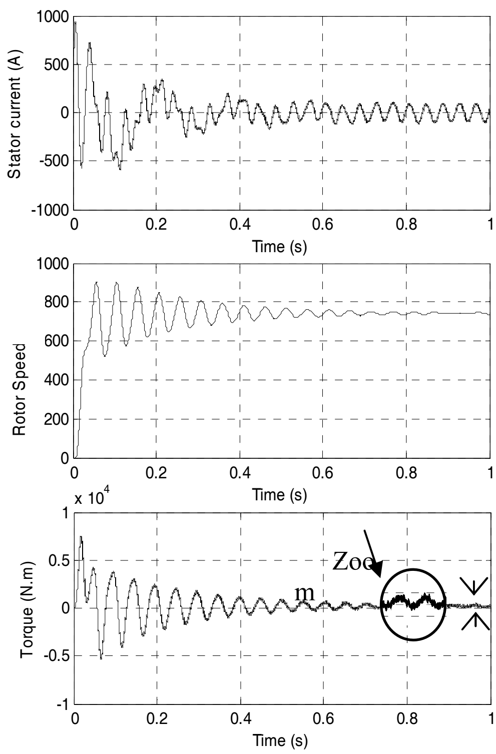

Fig. 4 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*25* Hz)

5.2. Results of Scalar control strategy (fo = 25 Hz)

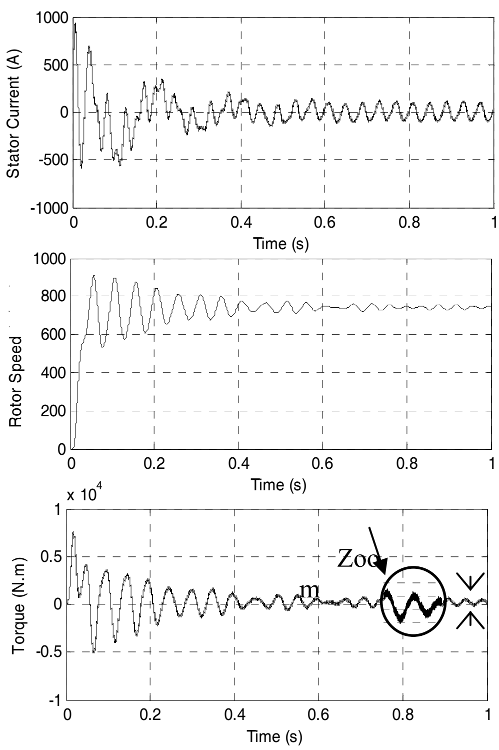

Fig. 6 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*25* Hz)

5.3. Results of Venturini method (f_o = 50 Hz)

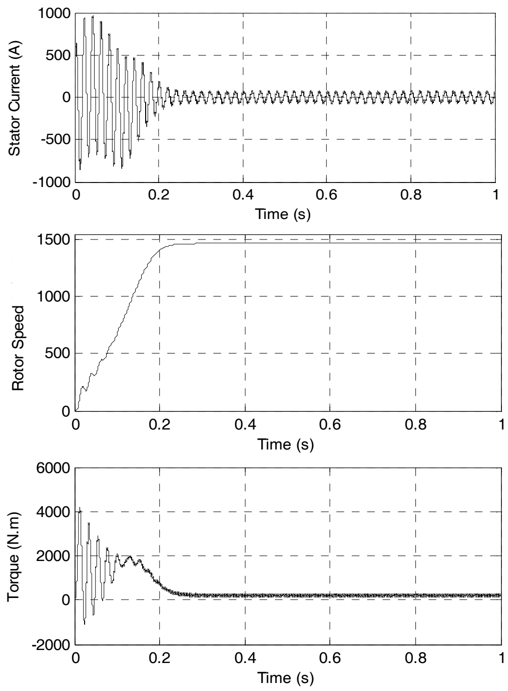

Fig. 7 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*50* Hz)

5.4. Results of Venturini method (f_o = *100* Hz)

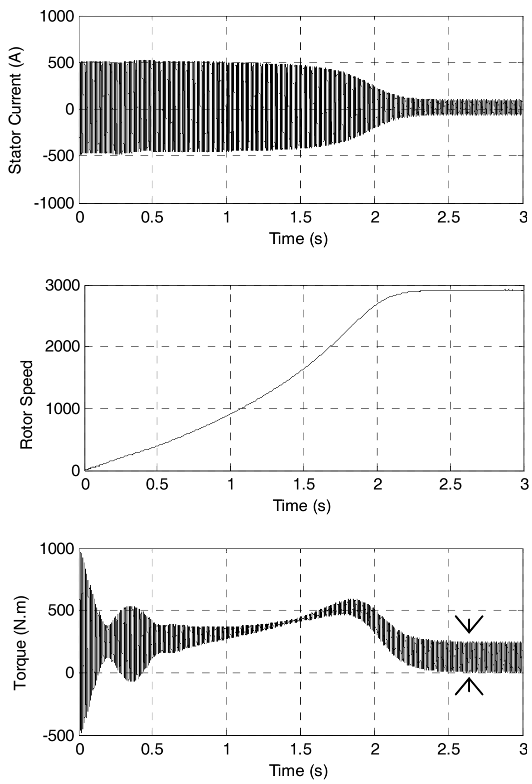

Fig. 8 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*100* Hz)

5.5. Results of Scalar control strategy (f_o = 50 Hz)

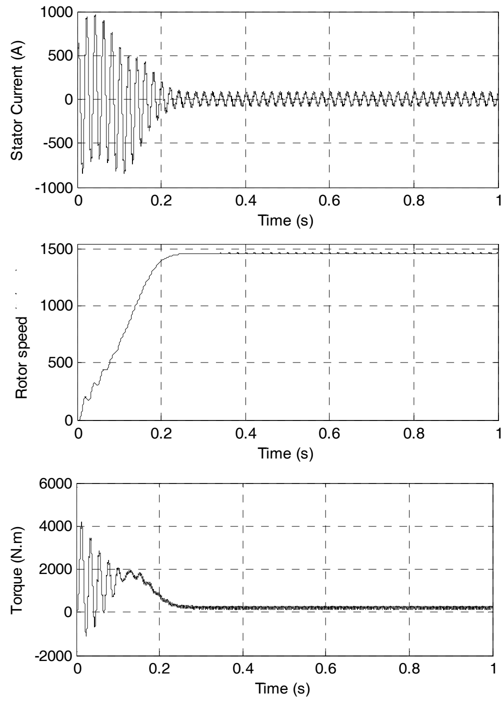

Fig. 9 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*50* Hz)

5.6. Results of Scalar control strategy (f_o = *100* Hz)

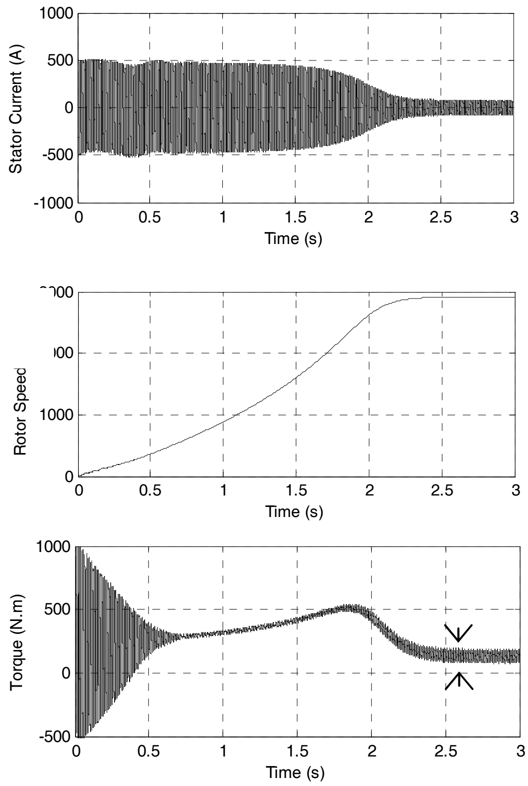

Fig. 10 Stator current, rotor speed, and torque for a matrix converter fed induction motor (f_o=*100* Hz)

6. CONCLUSION

In this article, a comparative study of two different control strategies is presented; the Venturini's and the Roy's strategies. Both techniques were applied to a three-phase matrix converter fed induction motor in the purpose to illustrate the performance of each one, and point out to the similarities and differences between them.

From the simulation results, with reference to the stator current, rotor speed and torque patterns obtained for the various values of frequency, one can deduce that choice of the strategy to use is predetermined by the comparison between the input supply frequency and the output (or desired) frequency of the matrix converter. If the input supply frequency is equal to the output frequency of the matrix converter, one can generally conclude that both techniques give almost similarly results. However, if the output frequency is lower than the supply network frequency, the choice is for the Venturini strategy and if the output frequency is superior to the supply network frequency, the Roy's strategy is preferred.

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