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Direct Control of Matrix Converters Using Asymmetric Strategy (ASVM) to Feed the Double Star Induction Machine

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Abstract: Due to their distinct advantages, the variable speed multi-phase drive systems are seen as serious contender to the existing three-phase drives. However we present in this work the modeling and control of matrix converter feeding a double star induction machine. In order to achieve this goal we present the model of matrix converter, and its control strategy: based on the direct space vector modulation (DSVM). Then we perform simulation tests for the whole converter and machine using *Matlab–Simulink*. The results illustrate the proper functioning of the system.

Keywords: *matrix converter; double star induction machine; space vector; modulation; switching strategies.*

Mathematics Subject Classification (2010): 68Q05, 93B52, 93C25, 93C83.

1 Introduction

To introduce an electric motor in high power applications, such as traction or marine propulsion, it is often necessary to segment the power. To this end, we can intervene at the converter level through multi-level techniques or parallel converters [7].

Another solution is to apply the segmentation level to the set converter-machine using multiphase machines. Indeed, the total power is distributed over a larger number of inverter arms, each of which is fed with a decreased power, which allows for a higher switching frequency and a less important ripple current and torque [2, 11]. One of the

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most common examples of multiphase machines is the double star induction machine (DSIM).

Such a machine has the advantage of reducing the electromagnetic torque ripples and rotor losses significantly. The double star induction machine studied in this paper is a machine that has two systems of coupled three-phase windings in the stator fixed star and out of phase with each other at an γ ($\gamma = 30°$) and a mobile rotor similar to that of classical asynchronous machine. The two systems of stator phases are fed by two sources of power frequency and amplitude equal but out of phase with each other at an angle ($\delta = \gamma = 30°$). However, the machine AC (asynchronous) is traditionally controlled by a PWM inverter control, an alternative is the matrix converter. The main characteristics of MC are: Direct AC-AC polyphase power conversion, inherent bidirectional power flow capability, input/output sinusoidal waveforms with variable output voltage amplitude and frequency, input power factor control despite the load in the output side and a simple and compact power circuit because of the elimination of bulky reactive elements [1, 5, 6, 8]. Recently, the most popular control algorithm widely used in matrix converters is space vector modulation (SVM) that allows input current and output voltage to be independently controlled. The principal reason for this is the better harmonic performance that can be achieved using different switching strategies in each commutation period. Two versions for SVM are defined: the indirect modulation and the direct one. In this work, we adopt the direct modulation (DSVM) which is realized by asymmetrical switching strategy.

2 Modeling of the Double Star Asynchronous Machine

The DSIM consists of two three-phase windings in the stator shifted from each other by an angle of 30° and one three-phase rotor winding. The two stator windings are fed by two systems of voltage frequency and amplitude equal but out of phase with each other at an angle ($\delta = \gamma = 30°$). The windings are shown in the following (Figure 1):

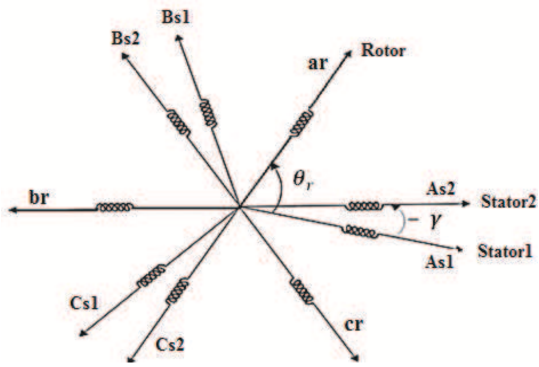

Figure 1: DSIM schema.

Park model of the double stator induction machines, with P pairs of poles, is defined by the following equations system (1).

$$[h]\begin{cases} V_{sd1} &= r_{s1}i_{sd1} + \dfrac{d\phi_{sd1}}{dt} - \omega_s\phi_{sq1}, \\ V_{sq1} &= r_{s1}i_{sq1} + \dfrac{d\phi_{sq1}}{dt} - \omega_s\phi_{sd1}, \\ V_{sd2} &= r_{s2}i_{sd2} + \dfrac{d\phi_{sd2}}{dt} - \omega_s\phi_{sq2}, \\ V_{sq2} &= r_{s2}i_{sq2} + \dfrac{d\phi_{sq2}}{dt} - \omega_s\phi_{sd2}, \\ 0 &= r_r r_{rd} + \dfrac{d\phi_{rd}}{dt} - (\omega_s - \omega_r)\phi_{rq}, \\ 0 &= r_r r_{rq} + \dfrac{d\phi_{rq}}{dt} - (\omega_s - \omega_r)\phi_{rq}. \end{cases} \tag{1}$$

The electromagnetic torque and speed are given by the following expressions (2):

$$\begin{cases} T_{em} = p\dfrac{L_m}{L_m + L_r}[\phi_{rd}(i_{sq1} + i_{sq2}) - \phi_{rq}(i_{sd1} + i_{sd2})], \\ J\dfrac{d\Omega}{dt} = C_{em} - C_r - K_f\Omega. \end{cases} \tag{2}$$

3 Matrix Converter Fundamentals

Recently there has been considerable interest in the potential benefits of matrix converter technology, especially for applications where size, weight, and long-term reliability are important factors [8]. For a three-phase to three-phase implementation, the matrix converter circuit consists of nine bidirectional switches so that any input line can be connected to any output line for any given length of time. The matrix converter used in the present work consists of two identical three-phase matrix converters. The schematic diagram of the converter is shown in Figure 2.

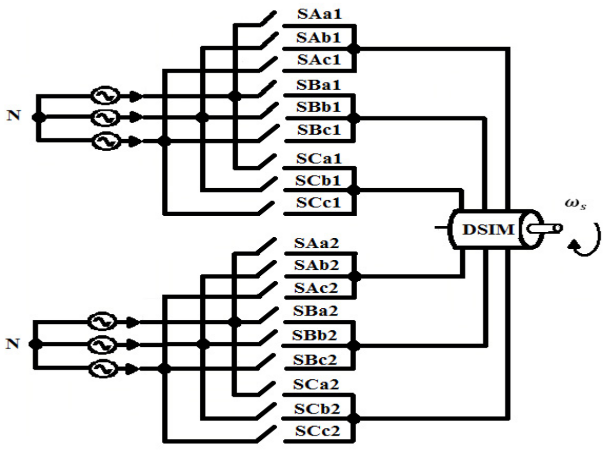

Figure 2: Schematic diagram of matrix converter-DSIM.

Each matrix is driven by three phase voltages (V_{Ak}, V_{Bk}, V_{Ck}) where a power is phase-shifted by 30° to each other, the double star induction motor load is connected to the output. The switching function of a switch SI_{j_k} is defined as (3):

$$SI_{j_k} = \begin{cases} 1 & switchs \quad SIj_k \quad closed \quad I = \{A, B, C\}, j = \{a, b, c\}, \\ 0 & switchs \quad SIj_k \quad closed \end{cases}, k = \{1, 2\}. \tag{3}$$

The mathematical expressions that represent the basic operation of the MC are obtained applying Kirchhoff's voltage and current laws to the switch array (4,5) [5, 6].

$$\begin{bmatrix} v_{ak}(t) \\ v_{bk}(t) \\ v_{ck}(t) \end{bmatrix} = \begin{bmatrix} SAak(t) & SBak(t) & SCak(t) \\ SAbk(t) & SBbk(t) & SCbk(t) \\ SAck(t) & SBck(t) & SCck(t) \end{bmatrix} \times \begin{bmatrix} V(t)_{Ak} \\ V(t)_{Bk} \\ V(t)_{Ck} \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} i_{Ak}(t) \\ i_{Bk}(t) \\ i_{Ck}(t) \end{bmatrix} = \begin{bmatrix} SAak(t) & SAbk(t) & SAck(t) \\ SBak(t) & SBbk(t) & SBck(t) \\ SCak(t) & SCbk(t) & SCck(t) \end{bmatrix} \times \begin{bmatrix} i(t)_{ak} \\ i(t)_{bk} \\ i(t)_{ck} \end{bmatrix}. \tag{5}$$

where v_{ak}, v_{bk} and v_{ck} $(k = 1, 2)$ are the output phase voltages, and i_{Ak}, i_{Bk} and i_{Ck} represent the input currents to the matrix. The output voltage is directly constructed switching between the input voltages and the input currents are obtained in the same way from the output ones. For these equations to be valid, the next expression (6) has to be taken into consideration:

$$\mathbf{S}_{Aj_k} + \mathbf{S}_{Bj_k} + \mathbf{S}_{Cj_k} = 1, j = \{a, b, c\}, \ (k = 1, 2). \tag{6}$$

What this expression says is that, at any time, one, and only one switch must be closed in an output branch. If two switches were closed simultaneously, a short circuit would be generated between two input phases. On the other hand, if all the switches in an output branch were open, the load current would be suddenly interrupted and, due to the inductive nature of the load, an over voltage problem would be produced in the converter.

4 Space Vector Approach

4.1 Modulation of MC

The Space Vector Modulation for MC is based on the instantaneous space vector representation of input currents and output voltages. SVM uses six sectors of the space, namely 1 to 6. The valid switching states (27) are shown in Table 1 [9, 10].

The first 18 switching states of Table 1 represent the active vectors and determine the output voltage vector v_o and input current vector which are presented in Figure 3.

The magnitude of these vectors depends upon the instantaneous values of the input current and output voltage. In these states any two output phases are connected to the same input phase. The remaining six switching states represent the zero vectors and each output phase is connected to a different input phase. Both the magnitude and the phase of the resultant rotating vectors are variable in these states.

4.2 Direct space vector modulation algorithm

In principle, the SVM algorithm is based on the selection of four active configurations which are applied for suitable time widths within each cycle period Tp. A zero configuration is then applied to complete Tp. At any cycle period, the output voltage vector

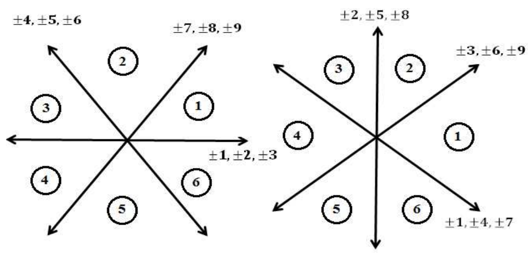

Figure 3: Output voltage and input current space vector hexagons.

States	Switches on	$\mid \overline{v_o} \mid$	$\angle\overline{v_o}$	$\mid \overline{i_i} \mid$	$\angle\overline{i_i}$
ABB +1	S_{Aa} S_{Bb} S_{Bc}	$+2/3V_{AB}$	0	$+2/\sqrt{3}i_a$	$-\pi/6$
BAA −1	S_{Ba} S_{Ab} S_{Ac}	$-2/3V_{AB}$	0	$-2/\sqrt{3}i_a$	$-\pi/6$
BCC +2	S_{Ba} S_{Cb} S_{Cc}	$+2/3V_{BC}$	0	$+2/\sqrt{3}i_a$	$\pi/2$
CBB −2	S_{Ca} S_{Bb} S_{Bc}	$-2/3V_{BC}$	0	$-2/\sqrt{3}i_a$	$\pi/2$
CAA +3	S_{Ca} S_{Ab} S_{Ac}	$+2/3V_{CA}$	0	$+2/\sqrt{3}i_a$	$7\pi/6$
ACC −3	S_{Aa} S_{Cb} S_{Cc}	$-2/3V_{CA}$	0	$-2/\sqrt{3}i_a$	$7\pi/6$
BAB +4	S_{Ba} S_{Ab} S_{Bc}	$+2/3V_{AB}$	$2\pi/3$	$+2/\sqrt{3}i_b$	$-\pi/6$
ABA −4	S_{Aa} S_{Bb} S_{Ac}	$-2/3V_{AB}$	$2\pi/3$	$-2/\sqrt{3}i_b$	$-\pi/6$
CBC +5	S_{Ca} S_{Bb} S_{Cc}	$+2/3V_{BC}$	$2\pi/3$	$+2/\sqrt{3}i_b$	$\pi/2$
BCB −5	S_{Ba} S_{Cb} S_{Bc}	$-2/3V_{BC}$	$2\pi/3$	$-2/\sqrt{3}i_b$	$\pi/2$
ACA +6	S_{Aa} S_{Cb} S_{Ac}	$+2/3V_{CA}$	$2\pi/3$	$+2/\sqrt{3}i_b$	$7\pi/6$
CAC −6	S_{Ca} S_{Ab} S_{Cc}	$-2/3V_{CA}$	$2\pi/3$	$-2/\sqrt{3}i_b$	$7\pi/6$
BBA +7	S_{Ba} S_{Bb} S_{Ac}	$+2/3V_{AB}$	$4\pi/3$	$+2/\sqrt{3}i_c$	$-\pi/6$
AAB −7	S_{Aa} S_{Ab} S_{Bc}	$-2/3V_{AB}$	$4\pi/3$	$-2/\sqrt{3}i_c$	$-\pi/6$
CCB +8	S_{Ca} S_{Cb} S_{Bc}	$+2/3V_{BC}$	$4\pi/3$	$+2/\sqrt{3}i_c$	$\pi/2$
BBC −8	S_{Ba} S_{Bb} S_{Cc}	$-2/3V_{BC}$	$4\pi/3$	$-2/\sqrt{3}i_c$	$\pi/2$
AAC +9	S_{Aa} S_{Ab} S_{Cc}	$+2/3V_{CA}$	$4\pi/3$	$+2/\sqrt{3}i_c$	$7\pi/6$
CCA −9	S_{Ca} S_{Cb} S_{Ac}	$-2/3V_{CA}$	$4\pi/3$	$-2/\sqrt{3}i_c$	$7\pi/6$
AAA 0_1	S_{Aa} S_{Ab} S_{Ac}	0	−	0	−
BBB 0_2	S_{Ba} S_{Bb} S_{Bc}	0	−	0	−
CCC 0_3	S_{Ca} S_{Cb} S_{Cc}	0	−	0	−

Table 1: Switching states and vectors used in DSVM.

v_o and the input current displacement angle φ_i are known as reference quantities. The input voltage vector is known from measured source voltage, the control of φ_i can be achieved controlling the phase angle β_i of the input current vector (Figure 4).

The modulation algorithm is explained using Figure 5 [9] representing the vectors, and i_i lie in sector 1. The reference voltage vector v_o is resolved into two components $v_o^{'}$ and $v_o^{''}$ along the two adjacent vectors. The $v_o^{'}$ component is synthesized using their two voltage vectors.

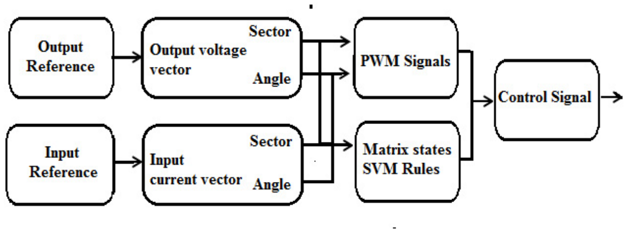

Figure 4: Modulation schema.

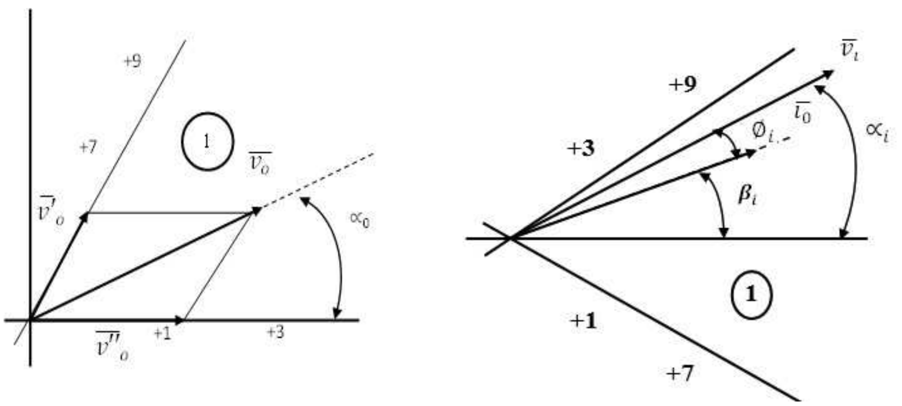

Figure 5: Modulation of the output voltage vectors and input current vectors.

The six switching states of $v_o^{'}$ are $\pm7, \pm8, \pm9$. Among the six possible switching states $(\pm7, \pm8, \pm9)$, the one that allows the modulation of the input current must be selected i.e. ±7 and ±9. Here the switching state ±8 of $v_o^{'}$ does not allow the modulation of the input current vector because the reference input current vector has the switching states of $\pm3, \pm6, \pm9$ and $\pm1, \pm4, \pm7$.

Therefore, the switching state ±8 is eliminated. From the remaining four switching states $(\pm7, \pm9)$, we assumed to apply the positive switching states $+7$ and $+9$. Similarly, the switching states required to synthesize the $v_o^{''}$ component can be selected as $+1$ and $+3$. Here ±2 is eliminated. The reference current vector i_i is resolved into two components $i_i^{'}$ and $i_i^{''}$ along the two adjacent vectors.

The $i_i^{'}$ component is synthesized using their two current vectors. The six switching states of $i_i^{'}$ are $\pm3, \pm6, \pm9$. Among the six possible switching states $(\pm3, \pm6, \pm9)$, the one that allows the modulation of the output voltage must be selected ±3 and ±6. Here the switching state ± 6 of $i_i^{'}$ does not allow the modulation of the output voltage vector because the reference output voltage vector has the switching states of $\pm 7, \pm 8, \pm 9$ and $\pm 1, \pm 2, \pm 3$. Therefore, the switching state 6 is eliminated. From the remaining four switching states $(\pm 3, \pm 9)$, we assumed to apply the positive switching states as $+3$ and $+9$. Similarly, the switching states required to synthesize the $i_i^{''}$ component can be selected as $+1$ and $+7$. Here ± 4 is eliminated.

Using the same procedure, it is possible to determine the four switches configurations correspondent to any possible combination of output voltage and input current sectors, which are quoted in Table 2 [10].

K_i \ K_v	1				2				3				4				5				6			
1	9	-7	-3	1	-6	4	9	-7	3	-1	-6	4	-9	7	3	-1	6	-4	-9	7	-3	1	6	-4
2	-8	9	2	-3	5	-6	-8	9	-2	3	5	-6	8	-9	-2	3	-5	6	8	-9	2	-3	-5	6
3	7	-8	-1	2	-4	5	7	-8	1	-2	-4	5	-7	8	1	-2	4	-5	-7	8	-1	2	4	-5
4	-9	7	3	-1	6	-4	-9	7	-3	1	6	-4	9	-7	-3	1	-6	4	9	-7	3	-1	-6	4
5	8	-9	-2	3	-5	6	8	-9	2	-3	-5	6	-8	9	2	-3	5	-6	-8	9	-2	3	5	-6
6	-7	8	1	-2	4	-5	-7	8	-1	2	4	-5	7	-8	-1	2	-4	5	7	-8	1	-2	-4	5
Duty	δ^{I}	δ^{II}	δ^{III}	δ^{IV}	δ^{I}	δ^{II}	δ^{III}	δ^{IV}	δ^{I}	δ^{II}	δ^{III}	δ^{IV}	δ^{I}	δ^{II}	δ^{III}	δ^{IV}	δ^{I}	δ^{II}	δ^{III}	δ^{IV}	δ^{I}	δ^{II}	δ^{III}	δ^{IV}

Table 2: Selection of active switching states for each combination of sector for output voltage K_V and input current K_I.

The required modulation duty cycles for switching states δ^I, δ^{II}, δ^{III} and δ^{IV} in the last row of Table 2 are given below:

$$\begin{aligned}
\delta^I &= \frac{2}{\sqrt{3}} \frac{V_O}{V_I} \frac{\cos(\widetilde{\alpha} - \frac{\pi}{3}) \cos(\widetilde{\alpha} - \frac{\pi}{3})}{\cos(\varphi_i)}, \\
\delta^{II} &= \frac{2}{\sqrt{3}} \frac{V_O}{V_I} \frac{\cos(\widetilde{\alpha} - \frac{\pi}{3}) \cos(\widetilde{\alpha} + \frac{\pi}{3})}{\cos(\varphi_i)}, \\
\delta^{III} &= \frac{2}{\sqrt{3}} \frac{V_O}{V_I} \frac{\cos(\widetilde{\alpha} + \frac{\pi}{3}) \cos(\widetilde{\alpha} - \frac{\pi}{3})}{\cos(\varphi_i)}, \\
\delta^{IV} &= \frac{2}{\sqrt{3}} \frac{V_O}{V_I} \frac{\cos(\widetilde{\alpha} + \frac{\pi}{3}) \cos(\widetilde{\alpha} + \frac{\pi}{3})}{\cos(\varphi_i)}.
\end{aligned} \tag{7}$$

Equations (7) have a general validity. For any combination of the output voltage sector K_v and the input current sector K_i (Table 2) provides the four switches configurations to be used within the cycle period Tp and equations (7) give the correspondent on-time ratios. In equations (7) the following angle limits apply:

$$-\frac{\pi}{6} < \widetilde{\alpha} < \frac{\pi}{6} \quad , \quad -\frac{\pi}{6} < \widetilde{\beta} < \frac{\pi}{6}.$$

For the feasibility of the control algorithm, the sum of the four on-time ratios must be lower than or equal to unity:

$$\delta^I + \delta^{II} + \delta^{III} + \delta^{IV} < 1. \tag{8}$$

4.3 Asymmetric switching strategies

Switching strategies deal with the switching configuration sequence, that is, the order in which the active and zero vectors are applied along the commutation period. The three zero configurations produce two degrees of freedom in order to complete the zero state switching time. In this paper one switching technique is simulated and analyzed: The Asymmetrical SVM (ASVM). The ASVM uses only one of the three zero configurations in the middle of the sequence so that minimum switch commutations are achieved between one switching state and the next one. Using this technique the switching commutations are up to 8 for each commutation period. In this way switching losses are minimized [5,6].

For example, considering both output voltage and input current reference vectors located in sector 1 within their respective hexagons, it can be seen that these are the only possible double-sided sequences that can be generated for ASVM techniques:

ACC-AAC-AAA-AAB-ABB | ABB-AAB-AAA-AAC-ACC

The zero configurations are obtained from Table 3 for ASVM:

i_{iref}	v_{oref} (1,2,3,4,5 or 6)
1 or 4	AAA
2 or 5	BBB
3 or 6	CCC

Table 3: Zero configuration for ASVM.

5 Simulation Results

5.1 Performance of the association matrix converter induction motor double star:

It directly feeds the induction machine double star by matrix converters. The simulation departs for startup vacuum after the steady state was established; we apply a torque load to the machine. The simulation results shown in Figure 6 represent the following quantities:

- The electromagntique torque.
- The speed of DSIM.
- Flux (ϕ_{rd} ,ϕ_{rq} and ϕ_r).

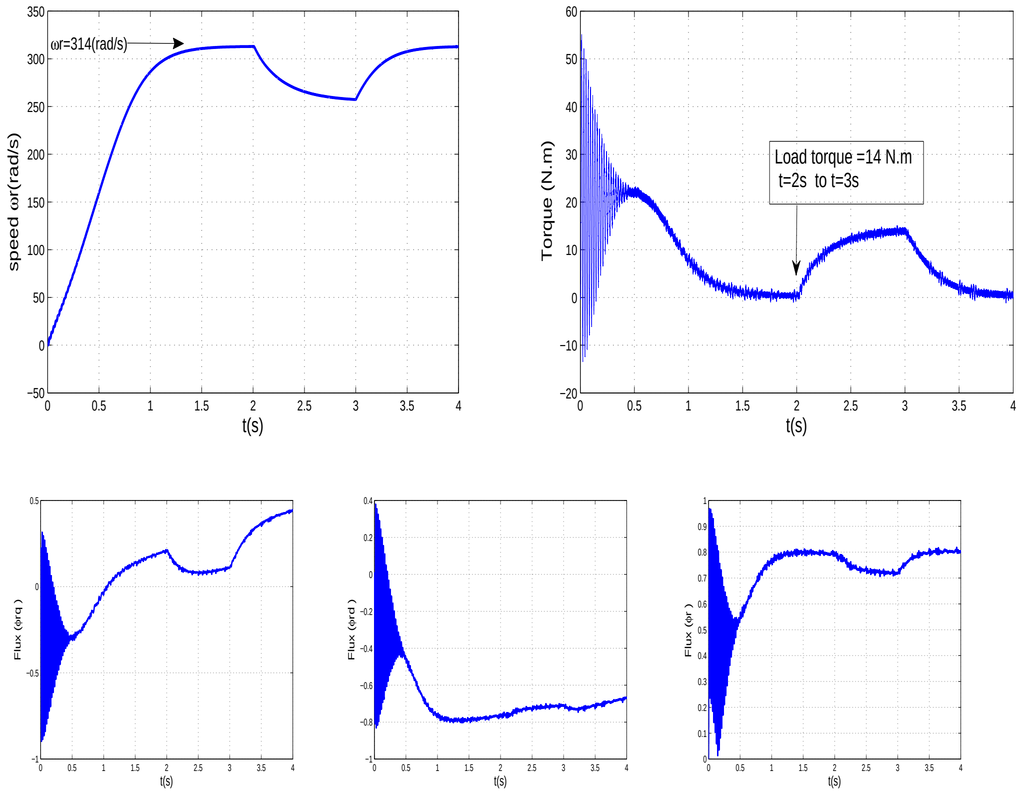

Figure 6: Performance of the association matrix converter double star induction machine controlled by Asymmetrical SVM

6 Conclusion

In this paper we have used the asymmetric strategy of space vector modulation to control directly the matrix converters, which feed a double-star induction machine. We can say that the matrix converter operates in the four quadrants. The performances obtained show that the proposed control strategy is distinguished by comparison with indirect converters (AC-DC-AC) by the reversibility of the converter. We can confirm that the benefits of using this type of converter are numerous; we include among other things, increasing the power, reduction of oscillations of the switching frequency of power switches and improved forms of output quantities.

Appendix

Double star induction machine parameters:

Pn=4.2KW, p=1, Ls1=0.011H, Ls2=0.011H, Lr=0.006H, Lm=0.3672H,
J=0.0625kG.m2, Kf=0.001 N.m.s/rad, Rs1=1.86Ω, Rs2=1.86Ω, Rr=2.12Ω.

switching frequency fs= 1/Ts = 10KHz.

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