

DIRECT TORQUE CONTROL BASED ON RST REGULATOR OF A DOUBLE STAR INDUCTION MACHINE

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Abstract- The paper discusses a direct torque control (DTC) strategy based on a RST regulator for double star induction machine (DSIM). The DTC is an excellent solution for general-purpose induction drives in very wide range. The short sampling time required by the DTC schemes makes them suited to a very fast torque and flux controlled drives as well the simplicity of the control algorithm. The DSIM is built with two symmetrical 3-phase armature winding systems, electrically shifted by 30°. A suitable transformation matrix is used to develop a simple dynamic model in view of control. The analysis of the torque in the stator flux linkage reference frame shows that the concept of DTC can be applied in DSIM. A set of voltage vectors corresponding to the switching mode are chosen to over a maximum voltage and keep the harmonics at a minimum. Further, a specific switching table for DSIM is proposed. Simulations results are given to show the effectiveness and the robustness of our approach.

Key words- Direct Torque Control “DTC”, doubly star induction machine, modelling, regulator RST, robustness, equations of state.

1. Introduction

AC machines with variable speed drives are widely employed in high power applications. In addition to the multilevel inverter fed electric machine drive systems [1], [2], one approach in achieving high power with [rating limited power electronic devices is the multiphase inverter system. In a multiphase inverter fed machine, the windings of more than three phases are connected in the same stator of the machine, consequently the current per phase in machine is reduced [3], [4].

The double stator induction machine needs a double three phase supply which has the many advantages. It minimise the torque pulsations and uses a power electronics components which allow a higher commutation frequency compared to the simple machines. However the double stator

induction machines supplied by a source inverter generate harmonic which results in supplementary losses [5]. The double star induction machine is not a simple system, because a number of complicated phenomena's appears in its function, as saturation and skin effects [6].

The double star induction machine is based on the principle of a double stators displaced by $\alpha=30^\circ$ and rotor at the same time. The stators are similar to the stator of a simple induction machine and fed with a 3 phase alternating current and provide a rotating flux.

Each star is composed by three identical windings and with their axes spaced by $2\pi/3$ in the space. Therefore, the orthogonality created between the two oriented fluxes, which must be strictly observed, leads to generate decoupled control within optimal torque [7].

This is a most rugged and maintenance free machine.

The machine studied is represented by with two stars windings: $A_{s1}B_{s1}C_{s1}$ et $A_{s2}B_{s2}C_{s2}$ which are displaced by $\alpha = 30^\circ$ and three rotorical phases: A_r, B_r, C_r .

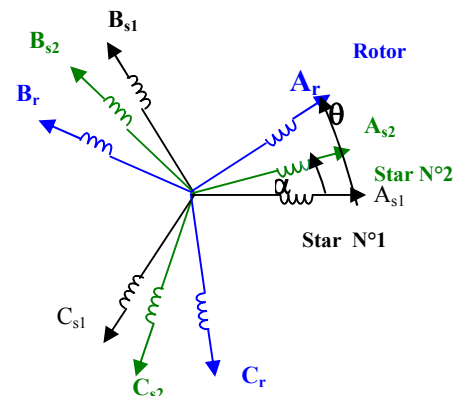


Fig.1 double star winding representation

2. Double star induction machine modelling

The mathematical model is written as a set of equations of state, both for the electrical and mechanical parts:

$$\begin{aligned} [V_{abc,s1}] &= [R_{s1}] [I_{abc,s1}] + \frac{d}{dt} [\Phi_{abc,s1}] \\ [V_{abc,s2}] &= [R_{s2}] [I_{abc,s2}] + \frac{d}{dt} [\Phi_{abc,s2}] \\ [V_{abc,r}] &= [R_r] [I_{abc,r}] + \frac{d}{dt} [\Phi_{abc,r}] \end{aligned} \quad (1)$$

$$J \frac{d\Omega}{dt} = C_{em} - C_r - K_f \Omega. \quad (2)$$

Where J is the moment of inertia of the revolving parts, K_f is the coefficient of viscous friction, arising from the bearings and the air flowing over the motor, and C_{em} is the load couple.

The electrical state variables are the flux, transformed into vector $[\Phi]$ by the “dq” transform, while the input are the “dq” transforms of the voltages, in vector $[V]$.

$$\frac{d}{dt} [\Phi] = [A] [\Phi] + [B] [V] \quad (3)$$

$$[\Phi] = \begin{bmatrix} \Phi_{ds1} \\ \Phi_{ds2} \\ \Phi_{qs1} \\ \Phi_{qs2} \\ \Phi_{dr} \\ \Phi_{qr} \end{bmatrix} \quad [V] = \begin{bmatrix} v_{ds1} \\ v_{ds2} \\ v_{qs1} \\ v_{qs2} \end{bmatrix} \quad (4)$$

The equation of the electromagnetic couple or torque as:

$$C_{em} = p \frac{L_m}{L_m + L_r} (\Phi_{dr} (i_{qs1} + i_{qs2}) - \Phi_{qr} (i_{ds1} + i_{ds2})) \quad (5)$$

The equations of flux are:

$$\left\{ \begin{aligned} \Phi_{md} &= L_a \left(\frac{\Phi_{ds1}}{L_{s1}} + \frac{\Phi_{ds2}}{L_{s2}} + \frac{\Phi_{dr}}{L_r} \right) \end{aligned} \right. \quad (6)$$

$$\left\{ \begin{aligned} \Phi_{mq} &= L_a \left(\frac{\Phi_{qs1}}{L_{s1}} + \frac{\Phi_{qs2}}{L_{s2}} + \frac{\Phi_{qr}}{L_r} \right) \end{aligned} \right. \quad (7)$$

Given that the “dq” axes are fixed in the synchronous rotating coordinate system, we have:

$$[A] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \quad (8)$$

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

Where:

$$\begin{aligned} a_{11} &= a_{33} = \frac{R_{s1} L_a}{L_{s1}^2} - \frac{R_{s1}}{L_{s1}} \\ a_{12} &= a_{34} = \frac{R_{s1} L_a}{L_{s1} L_{s2}} \\ a_{13} &= a_{24} = -a_{31} = -a_{42} = \omega_s \\ a_{14} &= a_{16} = a_{23} = a_{26} = a_{32} = a_{35} = a_{41} = a_{45} = a_{53} = \\ a_{54} &= a_{61} = a_{62} = 0 \\ a_{15} &= a_{36} = \frac{R_{s1} L_a}{L_r L_{s1}} \\ a_{21} &= a_{43} = \frac{R_{s2} L_a}{L_{s1} L_{s2}} \\ a_{22} &= a_{44} = \frac{R_{s2} L_a}{L_{s2}^2} - \frac{R_{s1}}{L_{s1}} \\ a_{25} &= a_{46} = \frac{R_{s2} L_a}{L_r L_{s2}} \\ a_{51} &= a_{63} = \frac{R_r L_a}{L_r L_{s1}} \\ a_{52} &= a_{64} = \frac{R_r L_a}{L_r L_{s2}} \end{aligned}$$

$$a_{55}=a_{66}=\frac{R_r L_a}{L_{r2}} - \frac{R_r}{L_r}$$

$$a_{56} = -a_{65} = \omega_{gl}$$

3. RST regulator structure

The RST is a polynomial regulator and is presented in the form of an interesting alternative to the classical PI regulator. The RST polynomial controller can improve the double feed induction machine performance in terms of overshoot, rapidity, cancellation of disturbance, and capacity to, maintain a high level of performances of machine speed.

The elements R, S and T are polynomials of which the degree is fixed according to the degree of the transfer functions of continuation and regulation in open loop. They are calculated using a strategy of robust placement of pole [8], [9].

The block-diagram of the RST controller is presented on figure. 1.

Where, A , B , R , S and T are polynomials of the variable "s" for the continuo system or "z" for the case of the discreet system.

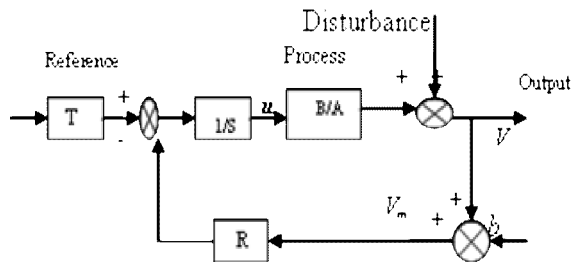


Fig.2. Block diagram of the Regulator

The process is described by the following transfer function:

$$G = \frac{B}{A} \quad (10)$$

The output verified the differentially equation

$$y = \frac{B}{A} U + d \quad (11)$$

We suppose that A and B are polynomials and d is the disturbance. $d^0(B) \leq d^0(A) = n$ Real.

The purpose of setting is to undo the mistake of Pursuit.

$$e = c - y \quad (12)$$

In fact, the output is measured by a sensor. It is flawed by a noise measurement b ; we have therefore:

$$y_m = y + b \quad (13)$$

Of (11), (12) and (13), we have:

$$\begin{aligned} S.U &= -R.y_m + T.c \\ &= -R.(y + b) + T.c \\ \Rightarrow T.c &= S.\left(\frac{A.y - A.d}{B}\right) + R.(y + b) \end{aligned} \quad (14)$$

$$\begin{aligned} B.T.c &= (A.S + B.R)y + R.B.b - A.S.d \\ \Rightarrow y &= \frac{B.T}{(A.S + B.R)}c - \frac{R.B}{(A.S + B.R)}b + \frac{A.S}{(A.S + B.R)}d \end{aligned} \quad (15)$$

Either $A.S + B.R$ the characteristic polynomial of the closed loop.

4. Resolution of «BEZOUT» equation

Accordance with Figure 1 and with the absence of noise measurement, we recall the closed loop equation leading to the transfer function:

$$y = \frac{B.T}{A.S + B.R}c + \frac{A.S}{A.S + B.R}d \quad (16)$$

The placement of poles is to specify the behaviour of $D(s)$ of the closed-loop, ie to calculate the polynomials R and S such as:

$$A.S + B.R = D \quad (17)$$

The resolution of polynomials R and S goes through solving the linear system, where the unknown are the coefficients of s of the polynomials. The choice of the degree of R and S is made in general with a proper regulator or strictly proper regulator.

For a proper regulator we have

$$d^0(R) = d^0(S)$$

$$d^0(R) = d^0(A)$$

$$d^0(D) = 2.d^0(A)$$

For a strictly proper regulator we have:

$$d^\circ(S) = d^\circ(R) + 1$$

$$d^\circ(S) = d^\circ(A) + 1$$

$$d^\circ(D) = 2.d^\circ(A) + 1$$

For a regulator strictly proper and with the following notions:

$$A(s) = s^n + a_1 s^{n-1} + \dots + a_n$$

$$B(s) = b_1 s^{n-1} + \dots + b_n$$

$$R(s) = r_0 s^n + r_1 s^{n-1} + \dots + r_n \quad (18)$$

$$S(s) = s_0 s^{n+1} + s_1 s^n + \dots + s_n s$$

$$D(s) = d_0 s^{2n+1} + d_1 s^{2n} + \dots + d_{2n+1}$$

That is the linear system according to Sylvester:

$$\begin{bmatrix} 1 & 0 & \dots & 0 & 0 & \dots & 0 \\ a_1 & 1 & \dots & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & b_1 & \dots & \vdots \\ \vdots & \vdots & \vdots & 0 & \vdots & \ddots & \vdots \\ a_n & \dots & \dots & 1 & \vdots & \dots & 0 \\ 0 & \dots & \dots & a_1 & b_n & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & 0 & \dots & b_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & a_n & 0 & \dots & \vdots \\ 0 & \dots & \dots & 0 & 0 & \dots & b_n \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \\ \vdots \\ s_n \\ r_0 \\ \vdots \\ r_n \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_n \\ d_{n+1} \\ \vdots \\ d_{2n+1} \end{bmatrix} \quad (19)$$

This system has a unique solution

The structure RST is a procedure that follow's position as methods of placing poles.

This structure permit specification poles of the closed loop for disturbance rejection and monitoring of the consign.

He properties of the rated performance and stability will depend on robust specifications polynomials R, S, T. It is therefore necessary to have a tool for choosing the closed-loop dynamic to answer this problem. A very fast dynamic doe's not lead necessary to a good robustness.[10]

We put the characteristic polynomial form

$$D(s) = P(s).F(s) \quad (20)$$

Where P(s) and F(s) are respectively the polynomials of the pursuit dynamical and the dynamical filter.

Therefore the polynomial T(s) is in the form of:

$$T(s) = \frac{R(0)}{F(0)} F(s) \quad (21)$$

The equation giving the transfer function for the Continuation and for the regulation become in this case:

$$y = \frac{B(s).T(s)}{P(s).F(s)} c + \frac{A(s).S(s)}{P(s).F(s)} d \quad (22)$$

$$y = \frac{B(s).R(0)}{P(s)F(0)} c + \frac{A(s).S(s)}{P(s).F(s)} d$$

The equation giving the transfer function for the Continuation and for the regulation become in this case:

5. Choice of roots

This time we will choose a pulse filter corresponding to a horizon filtering: T_f
 $\omega_c \omega_f \gg 1/\omega_f$

This pulsation is that from which we want the regulator Gain fall rapidly.

$$F(s) = (s + \omega_f)^{m-1} \quad (23)$$

6. Strategy of robust pole placement

In order to apprehend the concept of robustness we must be confined only to one particular parameter \mathbf{t} which is the margin of modulus and is very significant [11].

This margin of the module is defined as being the minimum remoteness place of Nyquist compared to the critical point and defines the margin of stability regarding uncertainties on the model of the process.

7.RST applied to doubly star induction machine

In a regulating polynomial with a regulator RST applied to the speed, and considering the torque load as perturbation, the simplified bloc system control is presented in fig.3

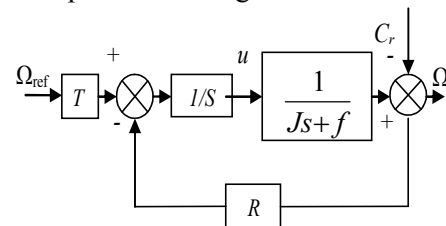


Fig. 3. Diagram block of regulation of speed of the DSIM

The transfer function of the system is given by:

$$G = \frac{1}{Js + f} \quad (24)$$

$$d^0(S) = 2d^0(A) + 1 = 2$$

The polynomial T in our case is fixed to a constant.

$$d^0(D) = 2d^0(A) + 1 = 3$$

We can have

$$R(s) = r_0s + r_1$$

$$D(s) = d_0s^3 + d_1s^2 + d_2s + d_3$$

$$S(s) = s_0s^2 + s_1s$$

We choose the Dynamic Stability arbitrary in closed loop as a result :

$$D(s) = (s+0.1238)(s+0.09854)(s+2.6210) \quad (25)$$

the Bezzout equation is a four equations with 4 unknown where the polynomial coefficient of D is linked to polynomial by R and S by the system matrix.

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & 1 & 0 & 0 \\ 0 & a_1 & b_1 & 0 \\ 0 & 0 & 0 & b_1 \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \\ r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

8. Direct torque control for the double star induction machine

The principle of a DTC consists to select stator voltage vectors according to the deference between the references of stator flux linkage and torque and their actual values. The DTC technique possesses advantages such as less parameter dependency, fast torque response and simple control scheme.

Direct torque control is based on the flux orientation, using the instantaneous values of voltage vector.

An inverter provide eight voltage vector, among which two are zeros [12],[13]. This vector are chosen from a switching table according to the flux and torque errors as well as the stator flux vector position. In this technique, we don't need the rotor position in order to chose the voltage vector. This particularity defines the DTC as an adapted control technique of ac machines and is inherently a motion sensor less control method [14],[15].

The block diagram for the direct torque and flux control applied to the double feed induction motor is shown in figure 4. The star flux Ψ_{ref} and the

torque C_{emref} magnitudes are compared with respective estimated values and errors are processed through hysteresis-band controllers.

Star flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory, and torque controller determinates the time duration of the zero voltage vectors, which keep the motor torque in the defined-by hysteresis tolerance band[16]. Finally, in every sampling time the voltage vector selection block chooses the inverter switching state, which reduces the instantaneous flux and torque errors.

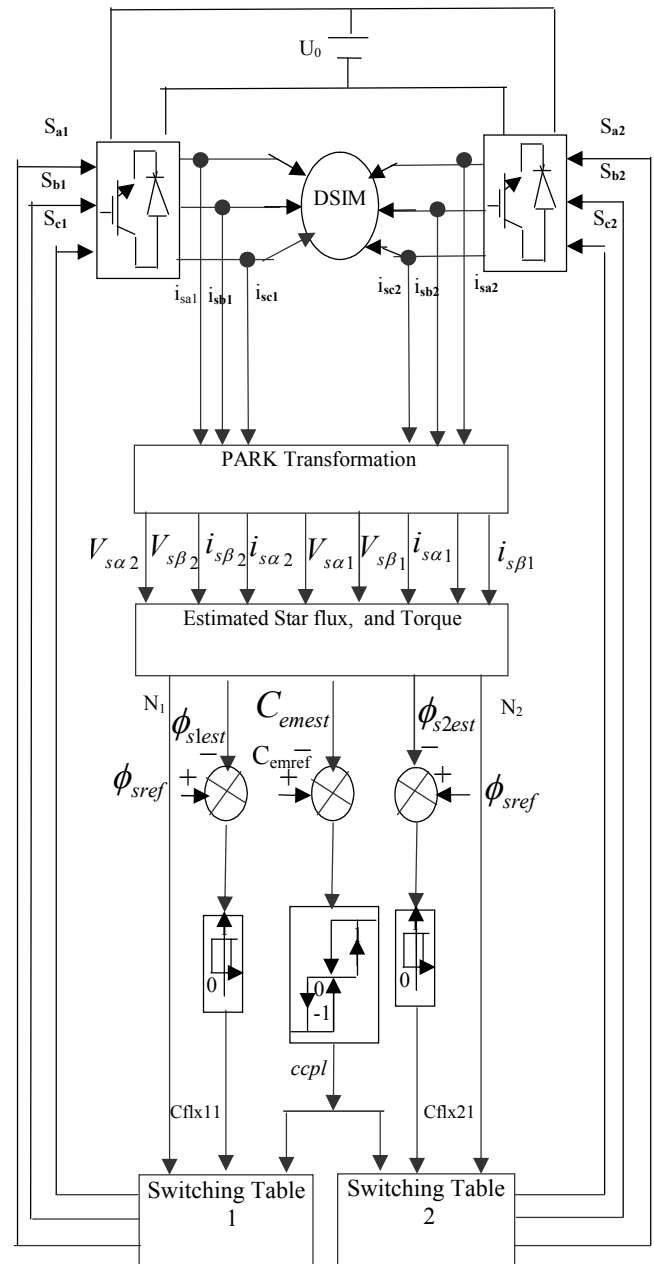


Fig.4: DTC applied to double star induction machine

The double star induction machines were afterward the object of an increasing interest, for different reason, such as:

The segmentation of power: as the double star induction machine contains two phases, thus for a given power, the currents by phases are decreased and this power is thus distributed on the number of the phases. ([17], [18]).

Improvement of the reliability by offering the possibility of working correctly in degraded regimes (one or several phases are opened), [5], so for example during functioning one of the arms of the inverter is defective, this case of desertion of the arm of the inverter raises no problem because there are at least three active phases. Thus more we increase the number of phases more we shall have a big range of freedom to control the machine.

9. Development of control Table

The control Table is built according to the state variables $cflx$ and $ccpl$, and the zone N_i of $\overline{\Phi_s}$ position .it has therefore the following form

Flux	Torque	N=1	N=2	N=3	N=4	N=5	N=6	Corrector
$cflx = 0$	$ccpl = 1$	V_3	V_4	V_5	V_6	V_1	V_2	Two level
	$ccpl = 0$	V_0	V_7	V_0	V_7	V_0	V_7	Three level
	$ccpl = -1$	V_5	V_6	V_1	V_2	V_3	V_4	
$cflx = 1$	$ccpl = 1$	V_2	V_3	V_4	V_5	V_6	V_1	Two level
	$ccpl = 0$	V_7	V_0	V_7	V_0	V_7	V_0	Three level
	$ccpl = -1$	V_6	V_1	V_2	V_3	V_4	V_5	

Table.1 Control strategy with Hysteresis comparator for a two levels (with zero voltage vector)

Flux	Torque	N=1	N=2	N=3	N=4	N=5	N=6	Corrector
$cflx = 0$	$ccpl = 1$	V_3	V_4	V_5	V_6	V_1	V_2	Two level
	$ccpl = 0$	V_4	V_5	V_6	V_1	V_2	V_3	Three level
	$ccpl = -1$	V_5	V_6	V_1	V_2	V_3	V_4	
$cflx = 1$	$ccpl = 1$	V_2	V_3	V_4	V_5	V_6	V_1	Two level
	$ccpl = 0$	V_1	V_2	V_3	V_4	V_5	V_6	Three level
	$ccpl = -1$	V_6	V_1	V_2	V_3	V_4	V_5	

Table.2. Control strategy with Hysteresis comparator for a Three levels (with no zero voltage vector)

Figure 5 refer in order, to the variation in magnitude of the following quantities, speed, stator current and electromagnetic torque obtained while starting up the induction motor initially under no load then connecting the nominal load. During the starting up with no load the speed rises rapidly its reference value without overtaking, however when the nominal load is applied a little overtaking is noticed and the command reject the disturbance. The excellent dynamic performance of torque and current control is evident.

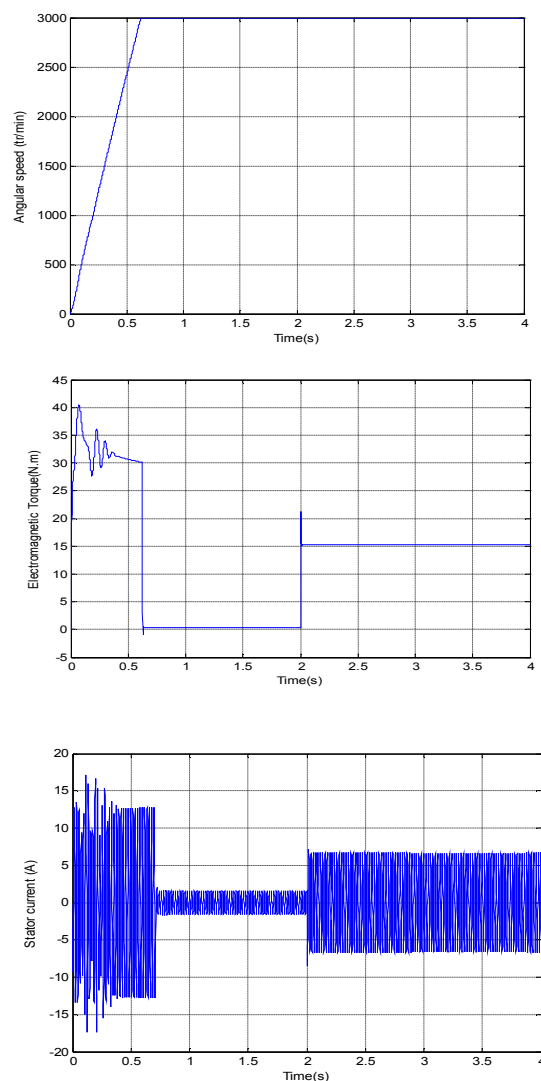


Fig. 5 Simulation results obtained

ROBUST CONTROL OF THE RST REGULATOR

A) Speed reversal of rated value

The excellent dynamic performance of torque control is evident in figure 6, which shows torque reversal for speed reversal of (3000, -3000 tr/min), with a load of 15N.m applied at $t=1.5$ s. The speed and torque response follow perfectly their reference values with the same response time. The reversal speed leads to a delay in the speed response, to a peak oscillation of the current.

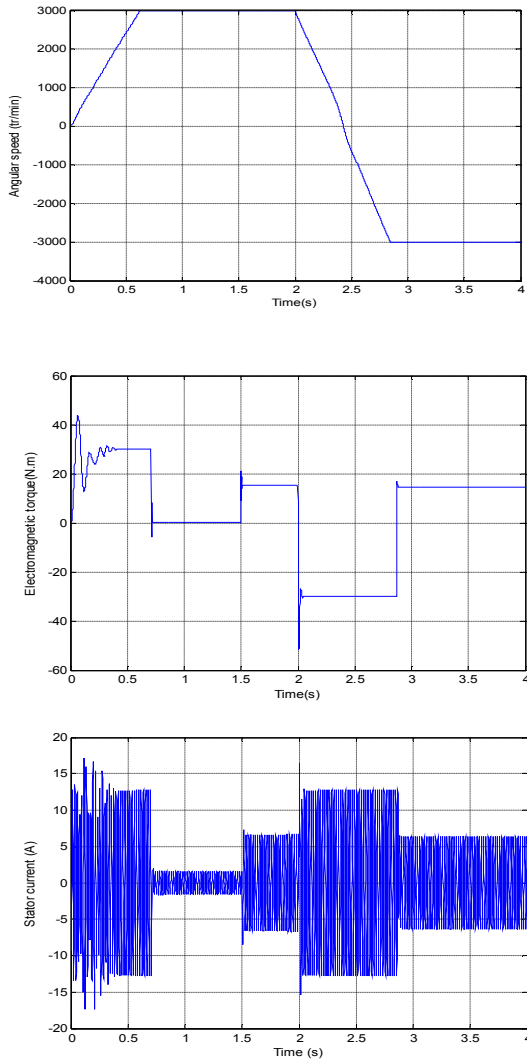


Fig 6. Robust control for a speed variation

b) Robust control for variable load

The simulation results obtained for a load variation ($C_r = [+15, -15, +10]$ N.m) in figure 7, show that the speed, the torque and the stator current are inflated with this variation. Indeed the torque and the speed follow their reference values.

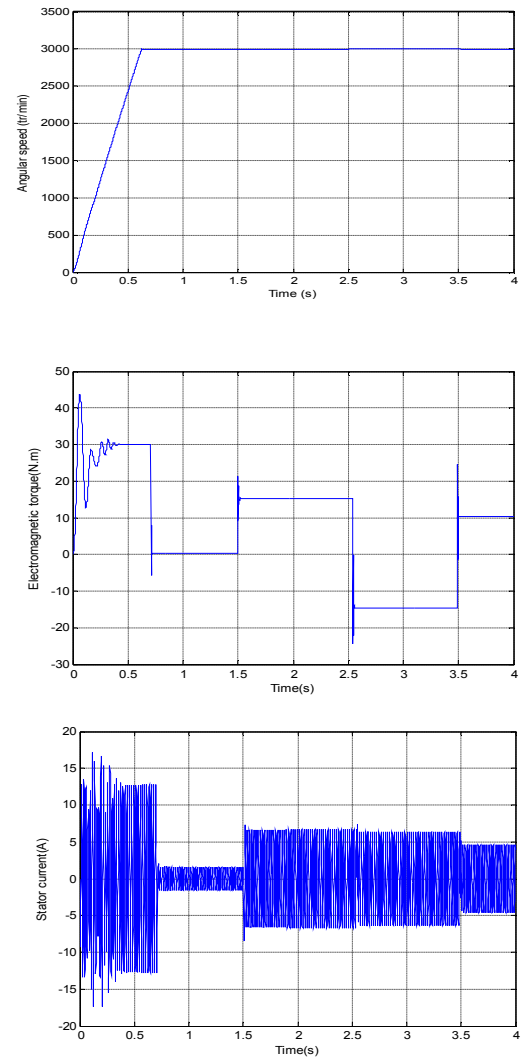


Fig 7. Robust control for a load variation

10. Conclusion

In this paper, we presented the direct control of the torque of the asynchronous double star machine supplied by two voltage inverters at two levels. This study presents a control strategy for a double star induction machine based on the direct torque control using an RST regulator. The simulation results show that the DTC is an excellent solution for general-purpose induction drives in a very wide power range. The short sampling time required by the DTC scheme makes it suited to very fast torque and flux controlled drives in spite of the simplicity of the control algorithm. We believe that the DTC principle will continue to play a strategic role in the development of high performance motion sensor less AC drives.

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