Acta Universitatis Apulensis No. 28/2011
ISSN: 1582-5329 pp. 351-366

COMPARATIVE STUDY BETWEEN A DOUBLE FED INDUCTION MACHINE AND DOUBLE STAR INDUCTION MACHINE USING DIRECT TORQUE CONTROL DTC

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Abstract. This paper describes the comparative study between two machines, a double fed induction machine and a double star induction machine, using direct torque control (DTC). In a double feed induction machine (DFIM), the stator is feed by a fixed network while the rotor by a variable supply which can be either a voltage or current source and in a double star induction machine needs a double three phase supply which has many advantages. 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. DTC is inherently a motion sensorless control method. The implementation of the DTC applied to a two machines is validated with simulated results.

1. Introduction

In the training domain of high power as the rolling mill, there is a new and original solution using a double feed induction machine (DFIM) and a double star induction machine (DSIM). In double fed induction machine, the stator is feed by a fixed network while the rotor by a variable supply which can be either a voltage or current source. The three phase induction motor with wound rotor is doubly fed when, as well as the stator windings being supplied with three phase power at an angular frequency ω_s, the rotor windings are also fed with three phase power at a frequency ω_{rr} . Under synchronous operating conditions, as shown in [1][2], the shaft turns at an angular velocity ω_r, such that:

$$\omega_r = \omega_s + \omega_{rr}$$

The sign on the right hand side is (+) when the phase sequences of the three phase supplies to the stator and rotor are in opposition and (-) when these supplies have the same phase sequence.

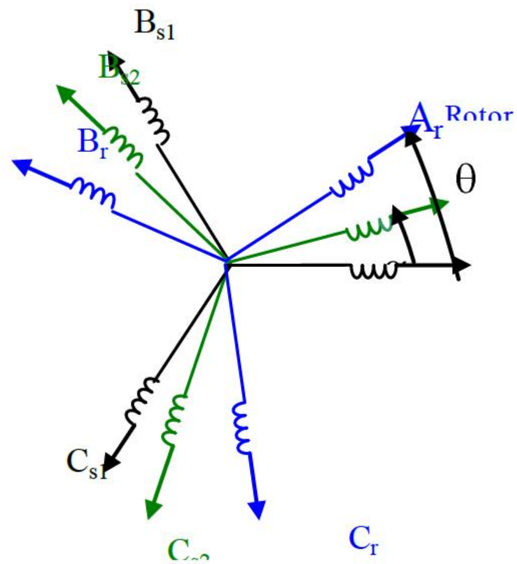

Figure 1: Double star winding representation

The double stator induction machine needs a double three phase supply which has many advantages. It minimise the torque pulsations and uses a power electronics components which allow a higher commutation frequency compared to the simple machines. The double star induction machine is not a simple system, because a number of complicated phenomena appear in its function, as saturation and skin effects [3].

The double star induction machine is based on the principle of a double stators displaced by $\alpha = 30$ 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 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 with an optimal torque [4]. This is a maintenance free machine.

The machine studied is represented with two stars windings: $A_{s1}B_{s1}C_{s1}$ and $A_{s2}B_{s2}C_{s2}$ which are displaced by $\alpha = 30$ and thee rotorical phases: $A_rB_rC_r$.

2.Double feed induction machine modeling

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

$$\frac{dX}{dt} = \dot{X} = AX + BU \tag{1}$$

Where:

$$X = \begin{bmatrix} I_{r\alpha} \\ I_{r\beta} \\ \Phi_{s\alpha} \\ \Phi_{s\beta} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \\ V_{r\alpha} \\ V_{r\beta} \end{bmatrix} \tag{2}$$

The matrices A and B are given by:

$$A = \begin{bmatrix} -\frac{1}{T_s'\delta} & \omega_r & \frac{1-\delta}{\delta M T_s} & \frac{1-\delta}{\delta M}\omega_r \\ -\omega_r & -\frac{1}{T_s'\delta} & -\frac{1-\delta}{\delta M}\omega_r & \frac{1-\delta}{\delta M T_s} \\ \frac{M}{T_s} & 0 & -\frac{1}{T_s} & 0 \\ 0 & \frac{M}{T_s} & 0 & -\frac{1}{T_s} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} -\frac{1-\delta}{\delta M} & 0 & \frac{1}{L_r\delta} & 0 \\ 0 & -\frac{1-\delta}{\delta M} & 0 & \frac{1}{L_r\delta} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{4}$$

$$J\frac{d\Omega}{dt} = C_{em} - C_r - K_f\Omega \tag{5}$$

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, C_{em} is the electromagnetic torque and C_r is the load couple.

The equation of the electromagnetic torque is:

$$C_e = \frac{3pM}{2L_s}(\Phi_{s\alpha}I_{r\beta} - \Phi_{s\beta}I_{r\alpha}) \tag{6}$$

3.Double star induction machine modelling

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

$$\begin{array}{l} \left[V_{abc,s1}\right] = \left[R_{s1}\right] + \left[I_{abc,s1}\right] + \frac{d}{dt}\left[\Phi_{abc,s1}\right] \\ \left[V_{abc,s2}\right] = \left[R_{s2}\right] + \left[I_{abc,s2}\right] + \frac{d}{dt}\left[\Phi_{abc,s2}\right] \\ \left[V_{abc,r}\right] = \left[R_r\right] + \left[I_{abc,r}\right] + \frac{d}{dt}\left[\Phi_{abc,r}\right] \end{array} \tag{7}$$

$$J\frac{d\Omega}{dt} = C_{em} - C_r - K_f\Omega \tag{8}$$

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 $[V]$.

$$\frac{d}{dt}[\Phi] = [A][\Phi] + [B][V] \tag{9}$$

$$[\Phi] = \begin{bmatrix} \Phi_{ds1} \\ \Phi_{ds2} \\ \Phi_{qs1} \\ \Phi_{qs2} \\ \Phi_{dr} \\ \Phi_{qr} \end{bmatrix}, \quad [V] = \begin{bmatrix} v_{ds1} \\ v_{ds2} \\ v_{qs1} \\ v_{qs2} \end{bmatrix} \tag{10}$$

The equation of the electromagnetic torque is given by

$$C_{em} = p\frac{L_m}{L_m + L_r}\big(\Phi_{dr}(i_{qs1} + i_{qs2}) - \Phi_{qr}(i_{ds1} + i_{ds2})\big) \tag{11}$$

The flux equations are:

$$\Phi_{md} = L_a\Big(\frac{\Phi_{ds1}}{L_{s1}} + \frac{\Phi_{ds2}}{L_{s2}}\frac{\Phi_{dr}}{L_r}\Big) \tag{12}$$

$$\Phi_{mq} = L_a\Big(\frac{\Phi_{qs1}}{L_{s1}} + \frac{\Phi_{qs2}}{L_{s2}}\frac{\Phi_{qr}}{L_r}\Big) \tag{13}$$

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

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

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{15}$$

Where:
$a_{11} = a_{33} = \frac{R_{s1}L_a}{L_{s1}^2} - \frac{R_{s1}}{L_{s1}}$

$a_{12} = a_{34} = \frac{R_{s1}L_a}{L_{s1}L_{s2}}$
$a_{13} = a_{24} = -a_{31} = -a_{42} = \omega_s$
$a_{14} = a_{16} = a_{23} = a_{26} = a_{32} = a = 35 = a_{41} = a_{45} = a_{53} = a_{54} = a_{61} = a_{62} = 0$
$a_{15} = a_{36} = \frac{R_{s1}L_a}{L_rL_{s1}}$, $a_{21} = a_{43} = \frac{R_{s2}L_a}{L_{s1}L_{s2}}$
$a_{22} = a_{44} = \frac{R_{s2}L_a}{L_{s2}^2} - \frac{R_{s1}}{L_{s1}}$, $a_{25} = a_{46} = \frac{R_{s2}L_a}{L_rL_{s2}}$
$a_{51} = a_{63} = \frac{R_rL_a}{L_rL_{s1}}$, $a_{52} = a_{64} = \frac{R_rL_a}{L_rL_{s2}}$
$a_{55} = a_{66} = \frac{R_rL_a}{L_{r2}^2} - \frac{R_r}{L_r}$, $a_{56} = -a_{65} = \omega_{gl}$

4.Direct torque control for the double star induction machine

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 [5],[6] .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 sensorless control method [7],[8].

Figure.2 shows the block diagram for the direct torque and flux control applied to the double star induction motor shown in. The star flux ref and the torque C_{emref} magnitudes are compared with estimated values respectively 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 [9], [10]. Finally, in every sampling time the voltage vector selection block chooses the inverter switching state, which reduces the instantaneous flux and torque errors [11].

5.Simulation results of a double fed induction machine

Figure 3 refer in order, to the variation in magnitude of the following quantities, speed, flux 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 reaches 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 flux control is evident.

5.1. Robust control of the regulator

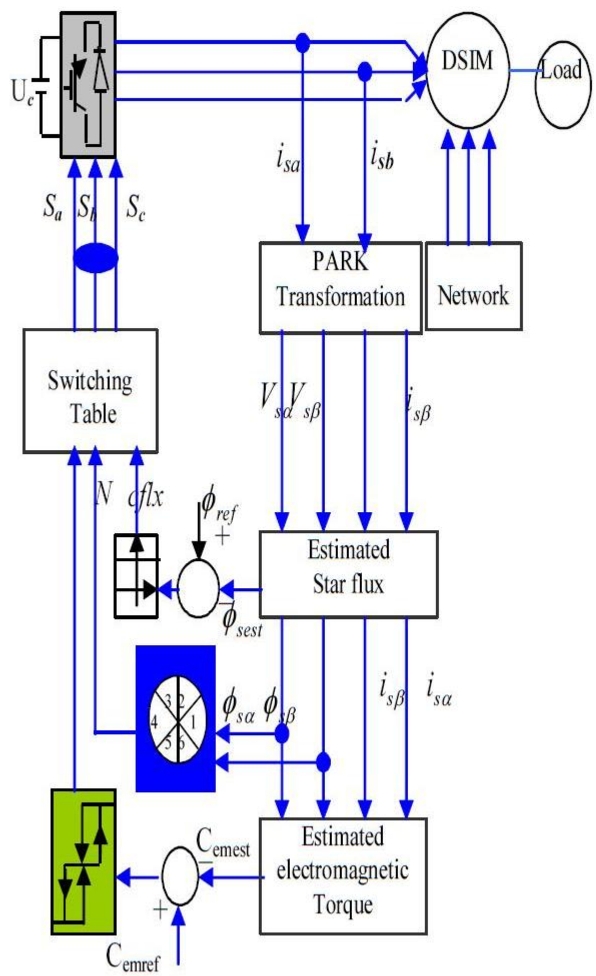

Figure 2: General structure of the DTC

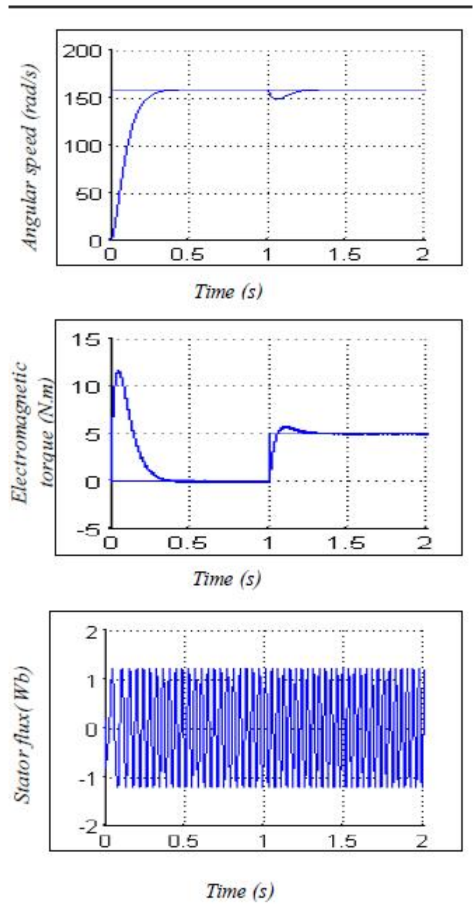

Figure 3: Simulation results obtained with an PI regulator

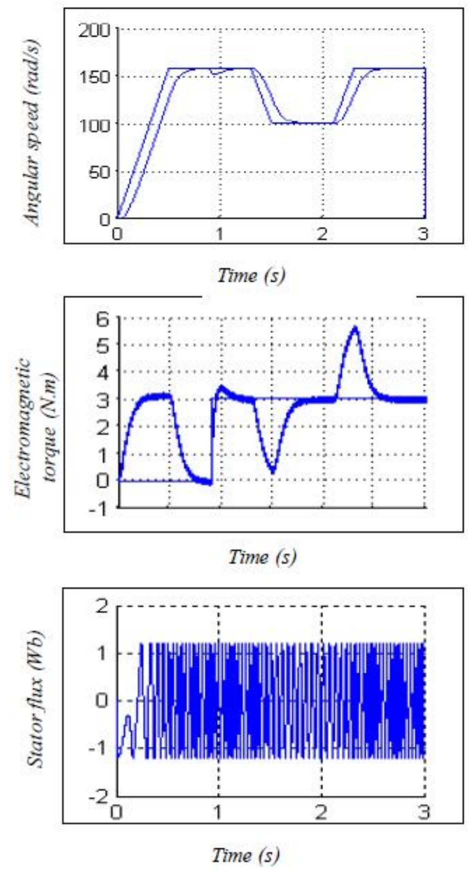

Figure 4: Robust control for a speed variation

A) Speed variation
Figure 4 shows the simulation results obtained for a speed variation for the values: (Ω_{ref}= 157, 100 and 157 rad/s), with the load of 3 $N.m$ applied at $t = 0.8s$. This results show that the variation lead to the variation in flux and the torque. The response of the system is positive, the speed follow its reference value while the torque return to its reference value with a little error.
B) Speed reversal of rated value
The excellent dynamic performance of torque control is evident in figure 5, which shows torque reversal for speed reversal of (157, -157 rad/s), with a load of $5N.m$ applied at $t = 1s$. 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

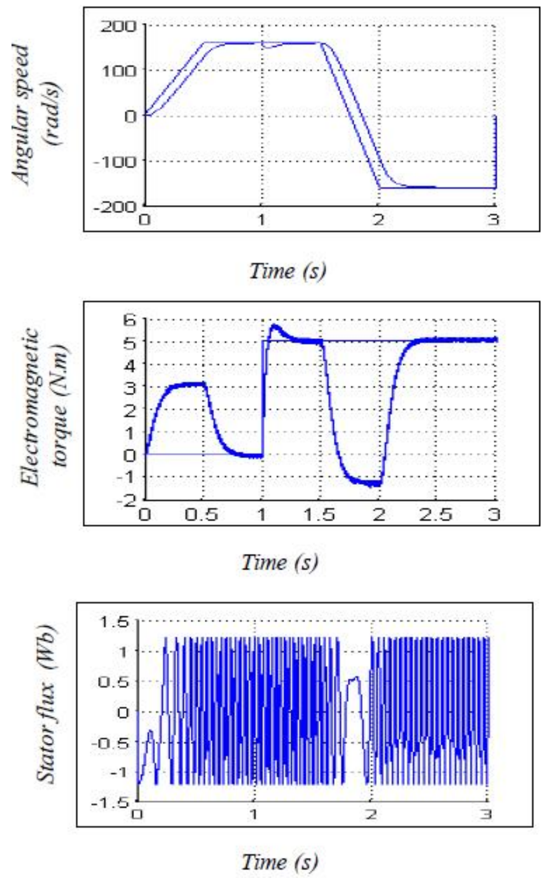

Figure 5: Robust control under reversal speed

response, to a peak oscillation the current as well as a fall in the flux magnitude which stabilize at its reference value.

C) Robust control for load variation

The simulation results obtained for a load variation ($C_r = 3N.m$, 6 $N.m$) in figure 6, show that the speed, the torque and the flux are inflated with this variation. Indeed the torque and the speed follow their reference values.

6.Simulation results of a double star induction machine

Figure 7 refer in order, to the variation of speed, electromagnetic torque, current and flux 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 recheas

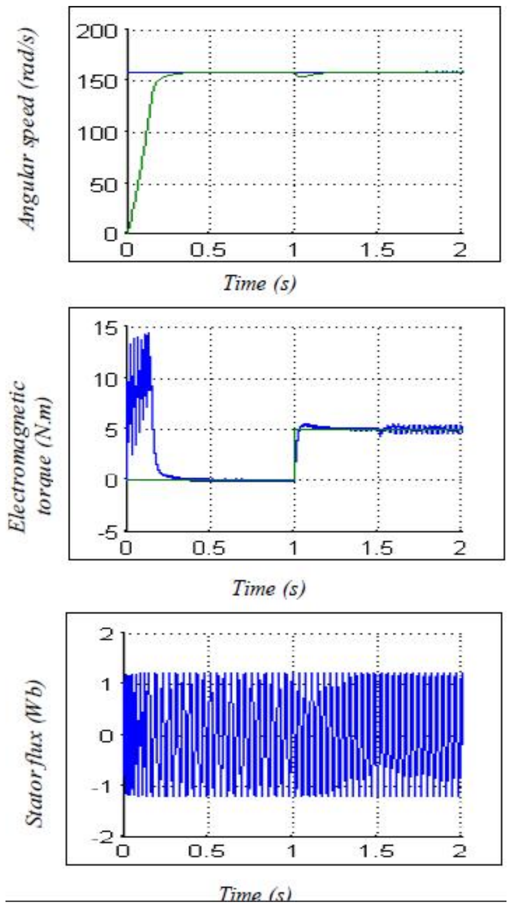

Figure 6: Robust control under stator resistance variation

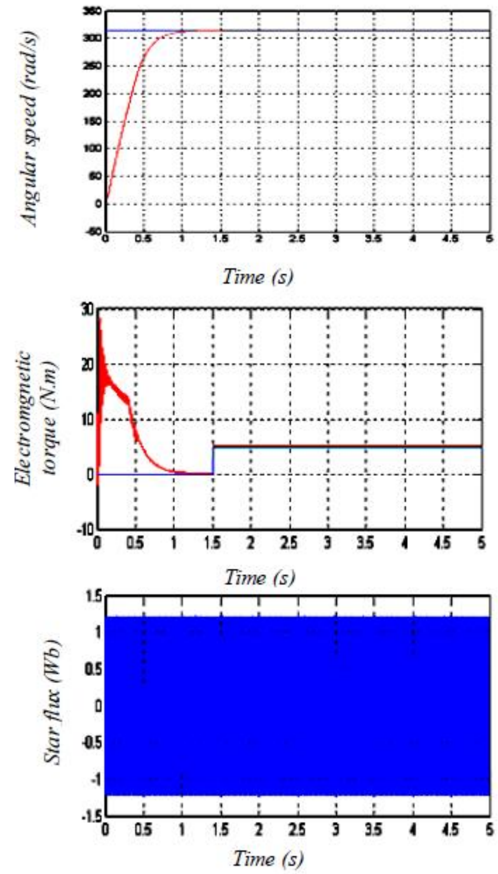

Figure 7: Simulation results obtained with an PI regulator

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 flux control is evident.

6.1. Robust control of the regulator

A) Speed variation

Figure.8 shows the simulation results obtained for a speed variation for the values: ($\Omega_{ref} = 314$ and $260 rad/s$), with the load of $5 N.m$ applied at $t = 1.5s$. These results shows that the variation load to the variation in flux and the torque. The response of the system is positive, the speed follow its reference value while the torque return to its reference value with a little error.

B) Speed reversal of rated value

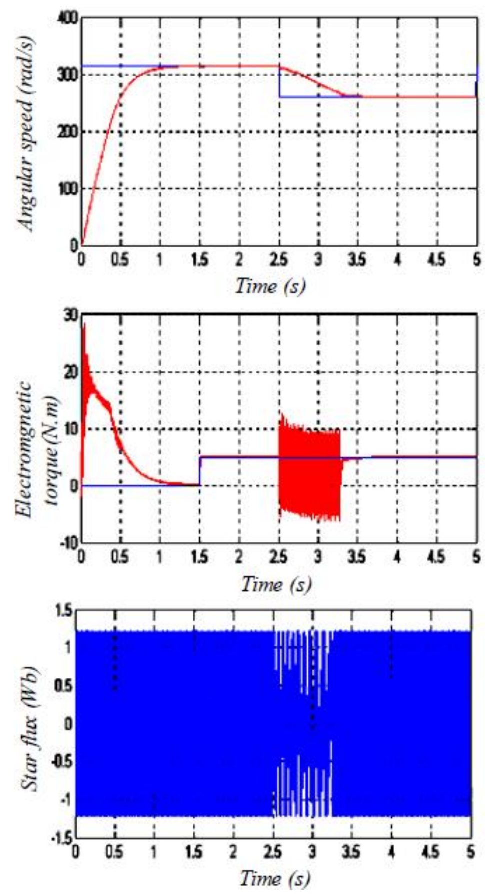

Figure 8: Robust control for a speed variation

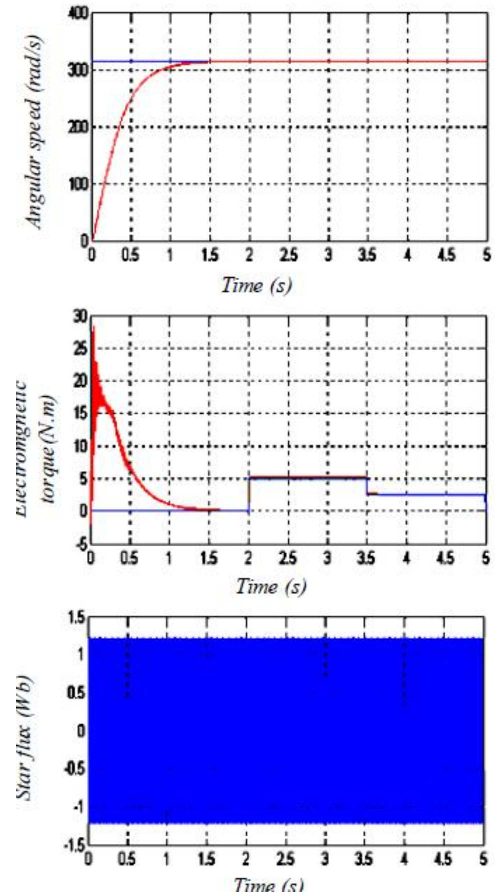

Figure 9: Robust control under load variation

Figure.9 shows the simulation results obtained for a load variation ($C_r = 5N.m$, $2.5N.m$). As can be seen the speed, the torque, the flux and current are influenced by this variation. The torque and the speed follow their reference values. We can see that the control is robust from the point of view load variation.

C) Robust control of the regulator under star resistance variation
In order to verified the robustness of the regulator under motor parameters variations we carried out a test for a variation of 50% in the value of star resistance at time $t = 1.5s$. The speed is fixed at $314 rad/s$ and a resistant torque of $5N.m$ is applied at $t = 1s$. Figure 10 shows in order the torque response, the current, the stator flux and the speed. The results indicate that the regulator is very sensitive to the resistance change which results in the influence on the torque and the stator flux

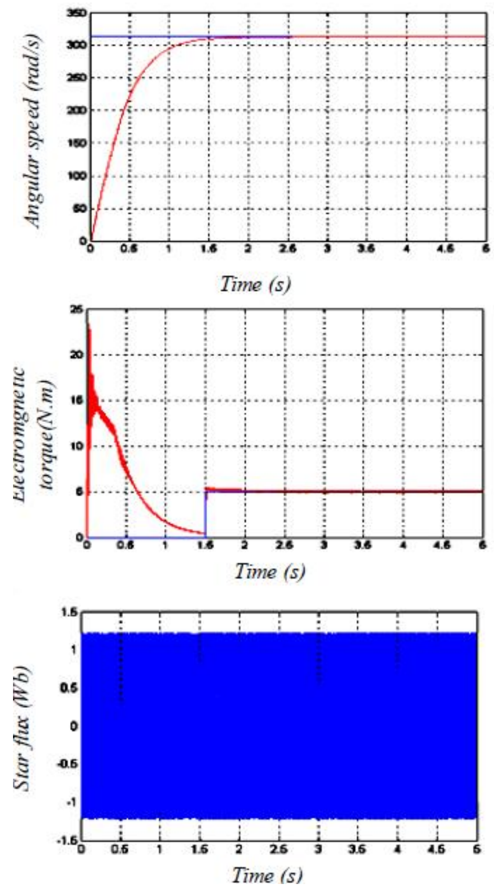

Figure 10: Robust control under star resistance variation

7. Conclusion

This paper presents comparative study between a double fed induction machine (DFIM) and double star induction machine(DSIM) based on the direct control torque (DTC) using a PI regulator. The simulation results show that the DTC is an excellent solution for general-purpose induction drives in a wide range of power. Simulation results on control robustness with speed variation, parameters variation and the torque resistant are given. The simulation results show that the DTC with a PI regulator present very good performances from the point of view robustness. The DTC control with a PI regulator offers as well a good dynamique and a very good precision. However when the statorique resistance change the robustness becomes weak. The simulation results show that the functioning of the DSIM is more stable with regard to the DFIM and where the answer of the electromagnetic torque does not present pulsations during the functioning of the machine, contrary to the functioning of the DFIM the torque presents weak oscillations. During the application of the load we also notice that this operation is almost ineffective on the DSIM with regard to the DFIM where the system accuses small abnormalities. However, from the point of view cost, the DSIM is more expensive than the DFIM and more than the number of phases increase more its coSt increases also. Of highly rated construction the DFIM is simpler than the DSIM.

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