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Comparative Study Direct Torque of Doubly Star Induction Motor (DSIM) by Using PI Controller and Fuzzy Logic Controller

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Abstract

This paper presents the simulation of the control of doubly star induction motor (DSIM) using direct torque controller (DTC) based on proportional integral controller (PI) and fuzzy logic controller (FLC). Double star induction motors are widely used in industrial applications where high reliability is required; there are many advantages of it compared to conventional method. It minimizes and reduces the torque pulsations and the current stress of each semiconductor power device by one half compared with the three-phase conventional induction motor. Extensive simulation results are presented from MATLAB/ Simulink environment. The system is tested at different speeds and a very satisfactory performance has been achieved.

Key Words: Direct torque control, Double star induction motor (DSIM), Fuzzy logic controller (FLC), PI controller.

1. Introduction

Asynchronous machines with variable speed drives are widely employed in high power applications. In addition to the multilevel inverter fed electric machine drive systems, one approach in achieving high power with rating limited power electronic devices is the multiphase inverter system [1,2]. In a multiphase inverter fed machine, the winding 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 [5, 7]. It minimise the torque pulsations and uses 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 $\alpha=30°$ 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 space [7,8].

Therefore, the orthogonality created between the two oriented fluxes, which must be strictly observed, leads to generate decoupled control within optimal torque [8,9].

2. Machine Modeling

The machine studied is represented by with two stators windings: A_{S1}, B_{S1}, C_{S1} and A_{S2} B_{S2} C_{S2} which are displaced by α=30° electrical angle and the rotor windings: A_r ,B_r, C_r.
The windings of the DSIM are shown in Fig . 1.

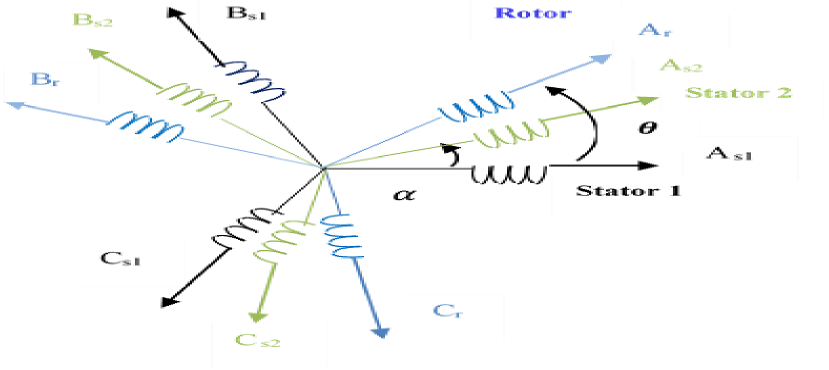

Fig. 1. Double star winding representation

The voltage equations for stator and rotor circuits for model of DSIM in the reference of Park are given by equation [1]:

$$
\begin{aligned}
V_{ds1} &= R_s I_{ds1} + \frac{d\emptyset_{ds1}}{dt} - \omega_s \emptyset_{qs1} \\
V_{qs1} &= R_s I_{qs1} + \frac{d\emptyset_{qs1}}{dt} + \omega_s \emptyset_{ds1} \\
V_{ds2} &= R_s I_{ds2} + \frac{d\emptyset_{ds2}}{dt} - \omega_s \emptyset_{qs2} \\
V_{qs2} &= R_s I_{qs2} + \frac{d\emptyset_{qs2}}{dt} + \omega_s \emptyset_{ds2} \\
0 &= R_r I_{dr} + \frac{d\emptyset_{dr}}{dt} - (\omega_s - \omega_r)\emptyset_{qr} \\
0 &= R_r I_{qr} + \frac{d\emptyset_{qr}}{dt} + (\omega_s - \omega_r)\emptyset_{dr}
\end{aligned}
\qquad (1)
$$

Where:

V_{ds1}, V_{qs1}, V_{ds2}, V_{qs2}: stator voltages dq components.

I_{ds1}, I_{qs1}, I_{ds2}, I_{qs2}, I_{dr}, I_{qr} : Stator currents dq components.

$\emptyset_{ds1}$, $\emptyset_{qs1}$, $\emptyset_{ds2}$, $\emptyset_{qs2}$, $\emptyset_{dr}$, $\emptyset_{qr}$: Stator and Rotor flux dq components.

The mechanical dynamic equation is given by:

$$J\frac{d\Omega_m}{dt} + f\Omega_m = T_e - T_r \qquad (2)$$

Where J is the moment of inertia of the revolving parts, f is the air flowing over the motor and T_{em} is the load Torque.
The electrical state variables are the flux transformed into vector [Ø] by the “dq” transform, while the input arethe “dq” transforms of the voltages, in vector [V].

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

$$[\emptyset] = \begin{bmatrix} \emptyset_{ds1} \\ \emptyset_{qs1} \\ \emptyset_{ds2} \\ \emptyset_{qs2} \\ \emptyset_{dr} \\ \emptyset_{qr} \end{bmatrix}, [V] = \begin{bmatrix} V_{ds1} \\ V_{qs1} \\ V_{ds2} \\ V_{qs2} \end{bmatrix}$$

The generated torque of doubly star induction can be expressed in terms of stator currents and stator flux linkage as :

$$T_{em} = p\frac{L_m}{L_m + L_r}\left[\phi_{dr}\left(i_{qs1} + i_{qs2}\right) - \phi_{qr}\left(i_{ds1} + i_{ds2}\right)\right] \qquad (4)$$

The equations of flux are:

$$\begin{cases}\phi_{md} = L_a(\frac{\phi_{ds1}}{L_{s1}} + \frac{\phi_{ds2}}{L_{s2}} + \frac{\phi_{dr}}{L_r}) \\ \phi_{mq} = L_a(\frac{\phi_{qs1}}{L_{s1}} + \frac{\phi_{qs2}}{L_{s2}} + \frac{\phi_{qr}}{L_r})\end{cases} \qquad (5)$$

$$L_a = \frac{1}{\frac{1}{L_{s1}}+\frac{1}{L_{s2}}+\frac{1}{L_r}+\frac{1}{L_m}} \qquad (6)$$

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

$$\begin{cases}\phi_{sd1} = L_{s1}i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{sq1} = L_{s1}i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{cases}$$
$$\begin{cases}\phi_{sd2} = L_{s2}i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{sq1} = L_{s2}i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{cases} \qquad (7)$$
$$\begin{cases}\phi_{dr} = L_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{sq1} = L_r i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{cases}$$

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

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Where:

$$a_{11} = a_{33} = \frac{R_{s1}L_a}{L_{s1}^2} - \frac{R_{s1}}{L_{s1}}, = a_{12} = a_{34} = \frac{R_{s1}L_a}{L_{s1}L_{s2}}, a_{31} = a_{24} = -a_{13} = \omega_s$$

$$a_{21} = a_{43} = \frac{R_{s2}L_a}{L_{s1}L_{s2}}$$

$$a_{14} = a_{16} = a_{23} = a_{26} = a_{32} = a_{35} = a_{41} = a_{45} = a_{53} = a_{54} = a_{61} = a_{62} = 0$$

$$a_{15} = a_{36} = \frac{R_{s1}L_a}{L_r L_{s1}}, a_{22} = a_{44} = \frac{R_{s2}L_a}{L_{s2}^2} - \frac{R_{s1}}{L_{s1}}, a_{25} = a_{46} = \frac{R_{s2}L_a}{L_r L_{s2}}$$

$$a_{51} = a_{63} = \frac{R_r L_a}{L_r L_{s1}}$$

$$a_{52} = a_{64} = \frac{R_r L_a}{L_r L_{s2}}, a_{55} = a_{66} = \frac{R_r L_a}{L_r^2} - \frac{R_r}{L_r}, a_{56} = -a_{65} = \omega g_1$$

3. Direct Torque Control for The Double Star Induction Motor

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

An inverter provides eight voltage vectors, among which two are zeros [10, 11]. This vector is 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

choose the voltage vector. This particularity defines the DTC as an adapted control technique of AC machines and is inherently a motion sensorless control method [8, 12, 13].

Fig. 2. shows the block diagram for the direct torque and flux control applied to the double star induction motor shown in. The star flux $\O_{ref}$ and the torque T_{emref} magnitudes are compared with estimated values respectively and errors are processed through hysteresis-band controllers [16].

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].

Finally, in every sampling time the voltage vector selection block chose the inverter switching state, which reduces the instantaneous flux and torque errors [17].

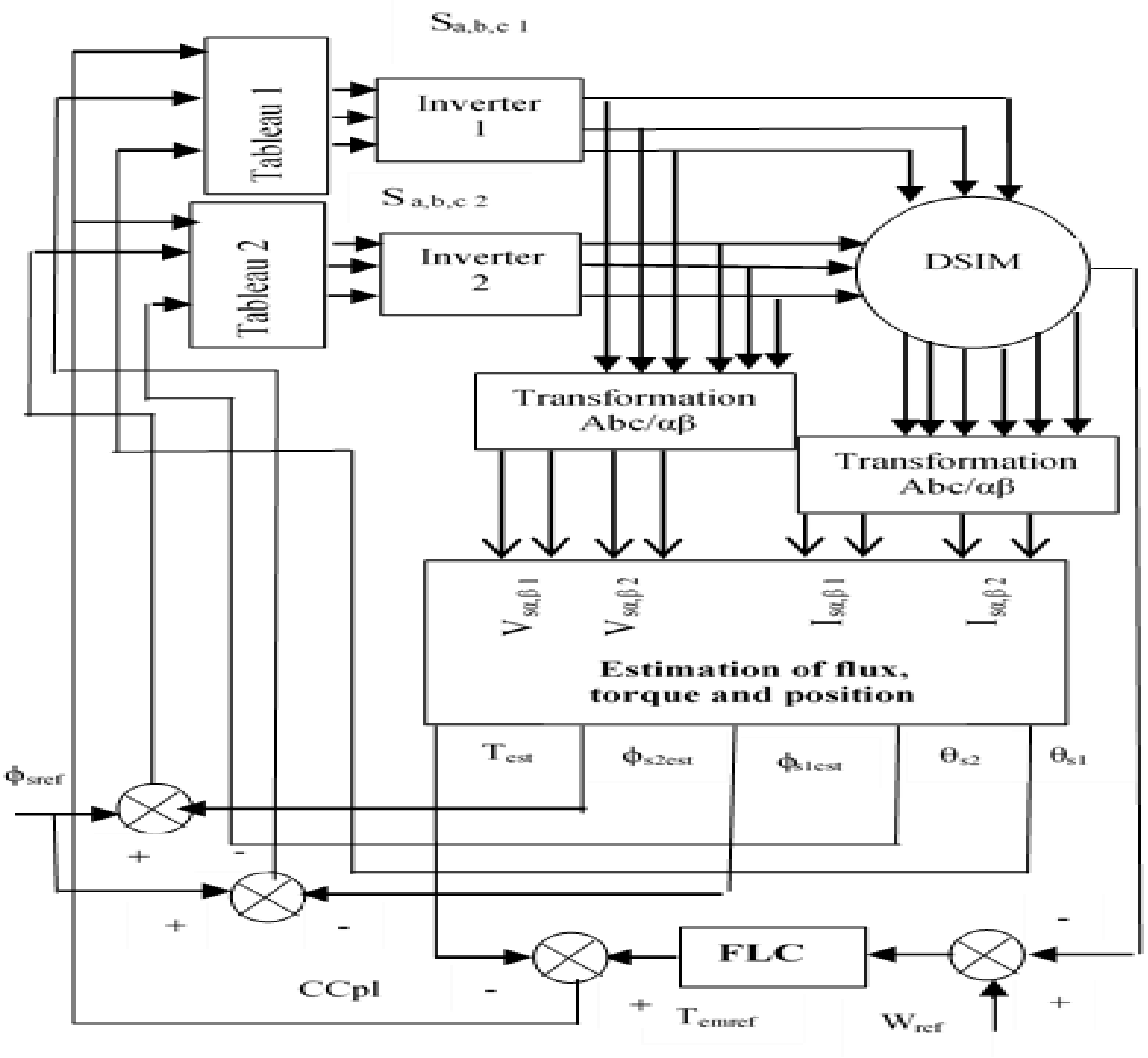

Fig. 2. Simulink model of DTC with fuzzy logic controller applied to doubly star induction machine (DSIM)

3.1. Torque and Flux Estimator

The feedback flux and torque are calculated from the machine terminal voltages and currents.

$$\begin{cases} V_{s\alpha1,2} = R_{s1,2} i_{s\alpha1,2} + \frac{d\emptyset_{s\alpha1,2}}{dt} \\ V_{s\beta1,2} = R_{s1,2} i_{s\beta1,2} + \frac{d\emptyset_{s\beta1,2}}{dt} \end{cases} \tag{8}$$

The expression of the stator flux is described by:

$$\begin{cases} \emptyset_{s\alpha1,2} = \int_0^t \left(V_{s\alpha1,2} - R_{s1,2} i_{s\alpha1,2}\right) dt, \\ \emptyset_{s\beta1,2} = \int_0^t \left(V_{s\beta1,2} - R_{s1,2} i_{s\beta1,2}\right) dt \end{cases} \tag{9}$$

The stator flux linkage phasors are given by:

$$\hat{\phi}_{s1,2} = \sqrt{\hat{\phi}_{s\alpha1,2}^{\,2} + \hat{\phi}_{s\beta1,2}^{\,2}} \tag{10}$$

The stator flux linkage phasors positions are:

$$\theta_{s1,2} = \mathrm{arctg}\frac{\hat{\phi}_{s\beta 1,2}}{\hat{\phi}_{s\alpha 1,2}} \tag{11}$$

The electromagnetic torque expressions are given by:

$$\hat{T_e} = \frac{3}{2}p\left(\hat{\phi}_{s\alpha}\, i_{s\beta} - \hat{\phi}_{s\beta}\, i_{s\alpha}\right) \tag{12}$$

4. Principe of Fuzzy Controller

The control by fuzzy logic permits to get a law of drive, often very effective, without having a precise model of the control strategy [14, 15]. Process, from a linguistic description of the performance of the system. Its strategy is different the one of the automatic classic [16, 17]. The fuzzy logic controller is a set of linguistic control rules associated by the dual concepts of fuzzy implication and the compositional rule of inference. The FLC provides an algorithm which can transfer the linguistic control approach based on expert knowledge into an automatic.
Block diagram of the FLC is shown in Fig. 3.

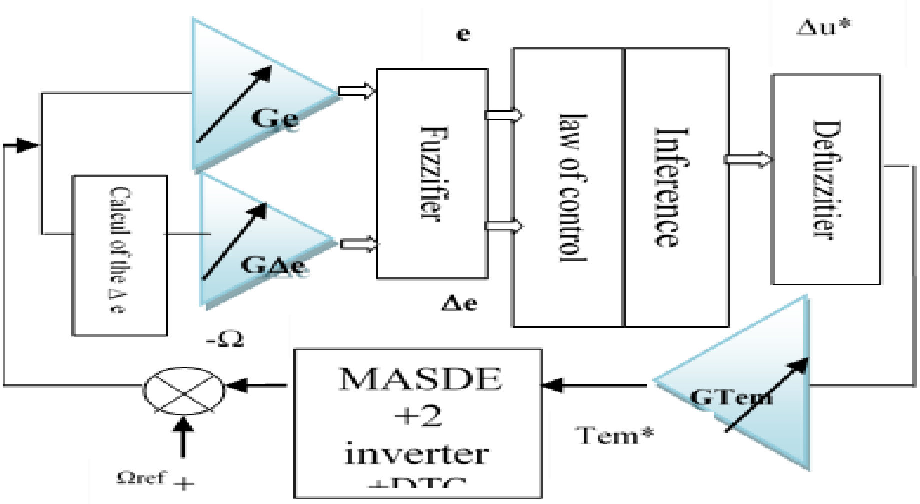

Fig. 3. Block diagram of fuzzy logic controller

Figure. 4. in which the linguistic variables are represented by NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big).
Table 1 shows one of possible control rules [17].

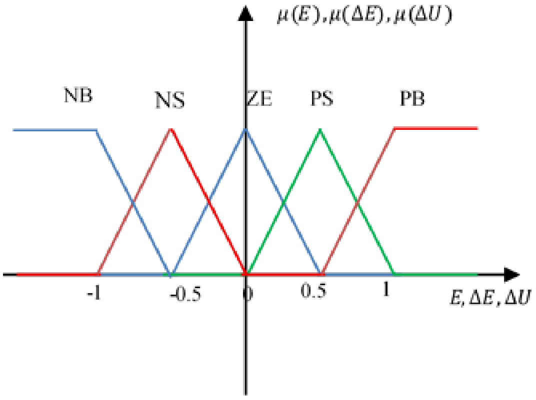

Fig. 4. Fuzzification with five memberships

Table. 1. Fuzzy control rule bases

E ΔE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

5. Results and Discussion

The simulation is done using MATLAB and results are presented here, the motor used in the simulation study is a 4.4 Kw. The parameters of the DSIM are summarized in Appendix.

1. Direct torque control with speed control:

Figures (5,6,7) represents the speed, electromagnetic torque and stator current responses. The comparison of the two controllers in terms of speed response demonstrates that the FLC has better performance and is more robust than the PI controller.

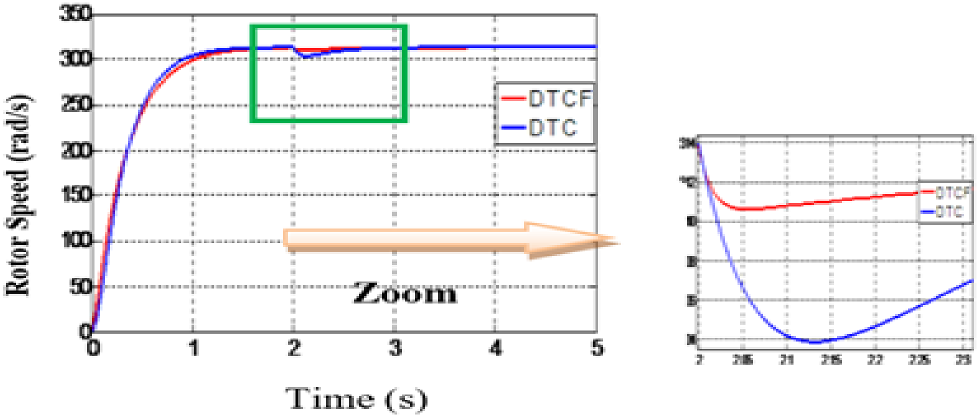

Fig. 5. Speed response by the PI and FLC of the DSIM with speed adjustment, followed by the application of a load Tr = 14N.m at t = 2 s.

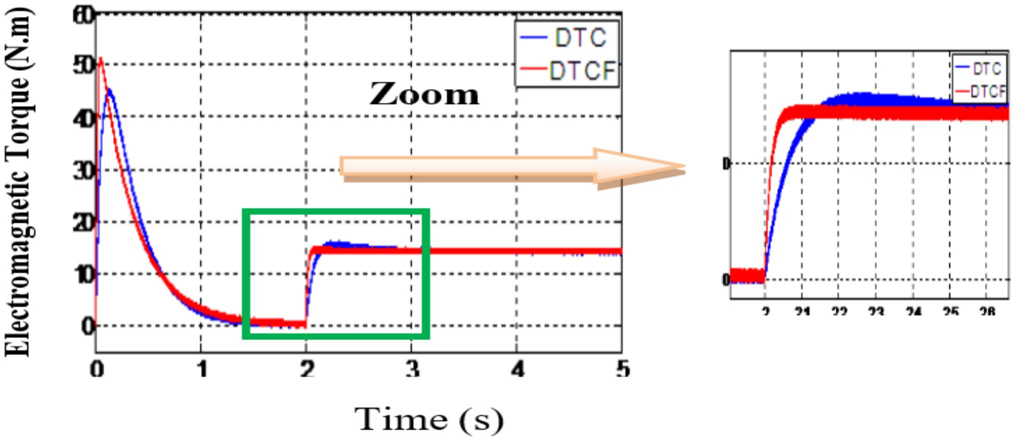

Fig. 6. Electromagnetic torque response by the PI and FLC of the DSIM with speed adjustment, followed by the application of a load Tr = 14N.m at t = 2 s.

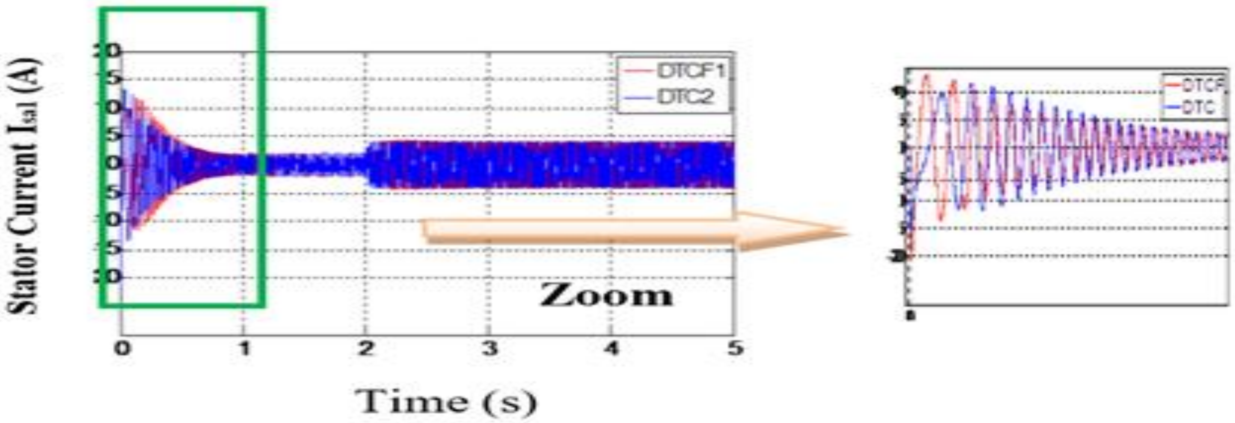

Fig. 7. Stator current response by the PI and FLC of the DSIM with speed adjustment, followed by the application of a load Tr = 14N.m at t = 2 s.

2 Robustness Test:

2. 1. Speed variation

The speed response, electromagnetic torque and stator current, for two control techniques of control, DTC with PI and FLC, are shown in Figures (8, 9, 10). Initially, the DSIM started at 314 rad/sec and underwent an abrupt change from 314 to 260 rad/sec at t=3.5s. It can be seen that the amplitude of the transient oscillations is minimized with the FLC due to its better disturbance rejection. Moreover, this result shows that the DSIM using the FLC has good quality and ensures stability under variable speed.

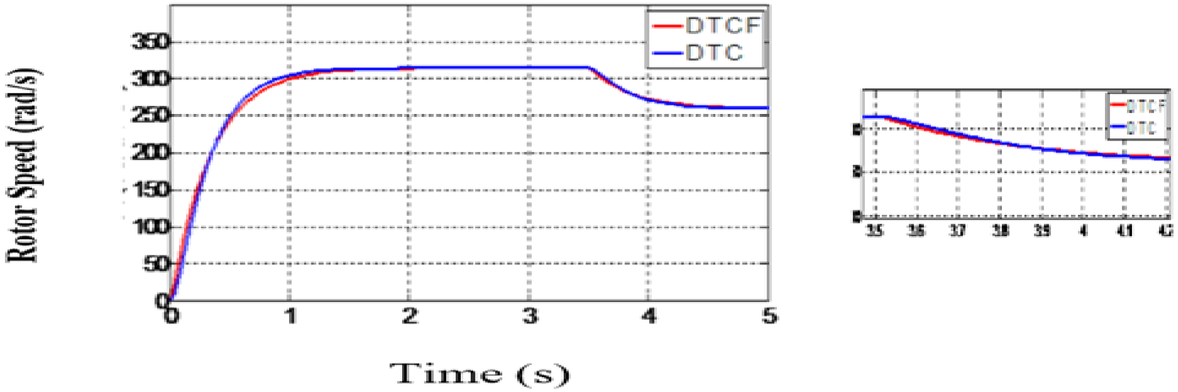

Fig. 8. Speed response of DSIM by PI controller and FLC

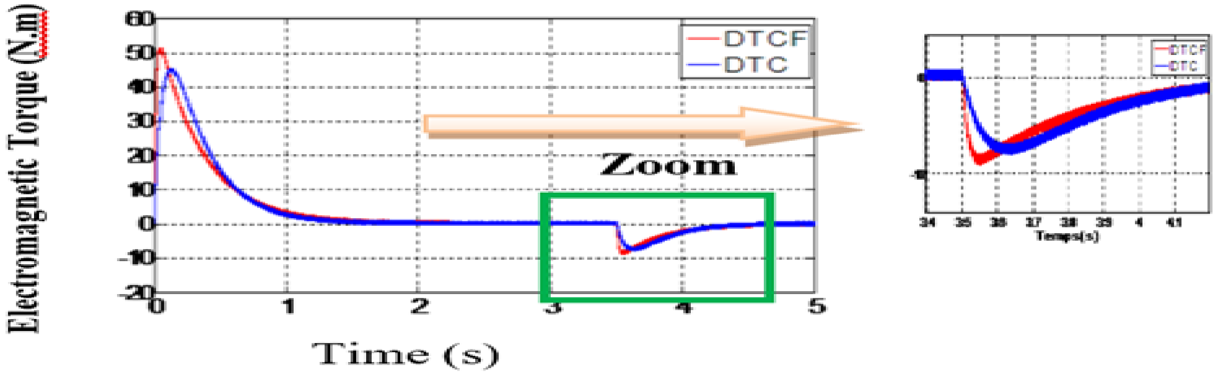

Fig. 9. Electromagnetic torque response of DSIM by PI controller and FLC

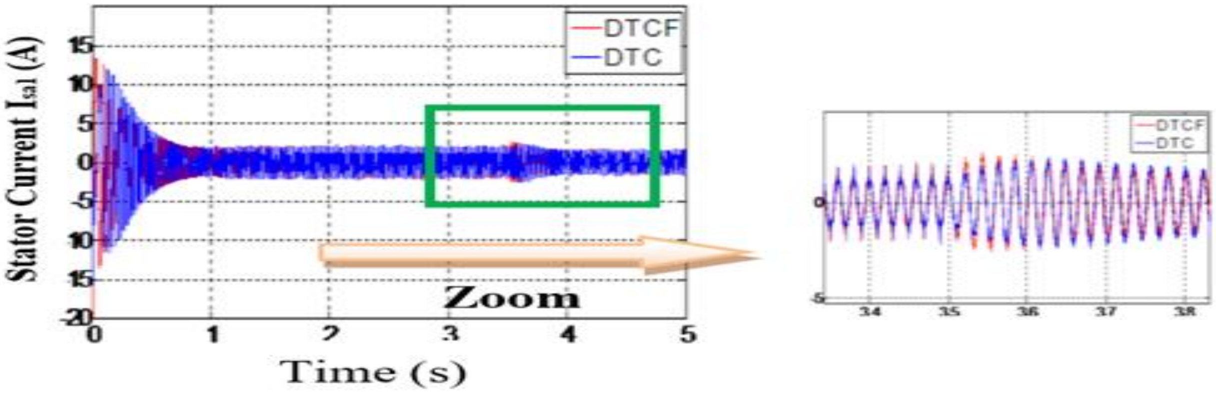

Fig. 10. Stator current of by the PI and FLC of the DSIM

2.2. Torque variation

Figure (11,12,13). shows the results of simulation, speed, electromagnetic torque, and stator current responses obtained for a load variation (Cr=15N.m, 20N.m) for the period of the interval [2 - 3.5] s, and the DSIM runs with speed values (314 rad/s). We can see the responses for DTC of DSIM using the proposed PI and FLC, we note that when the motor starts, the speed reaches its reference speed (314 rad/s) , the mechanical torque increases to reach the peak value (45 N.m) with PI and (52 N.m) with FLC and falls down to be close zero value because the motor running with no load. At during [2 - 3.5] s we changed the value of load torque to Tr=15N.m, the motor output torque will increase to cover this load. The harmonics magnitude of electromagnetic torque produced by the FLC is inferior than produced by PI. The stator flux remains constant which explains the decoupling between flows and torque of the two controllers PI and FLC.

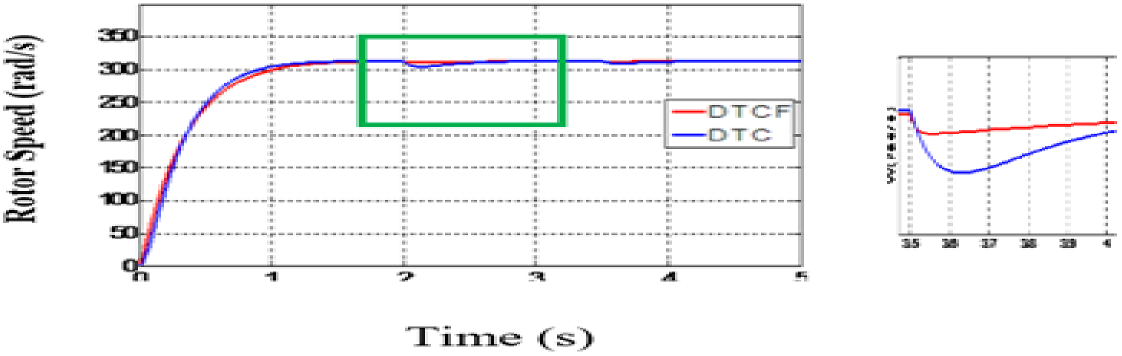

Fig. 11. Speed response of torque variation

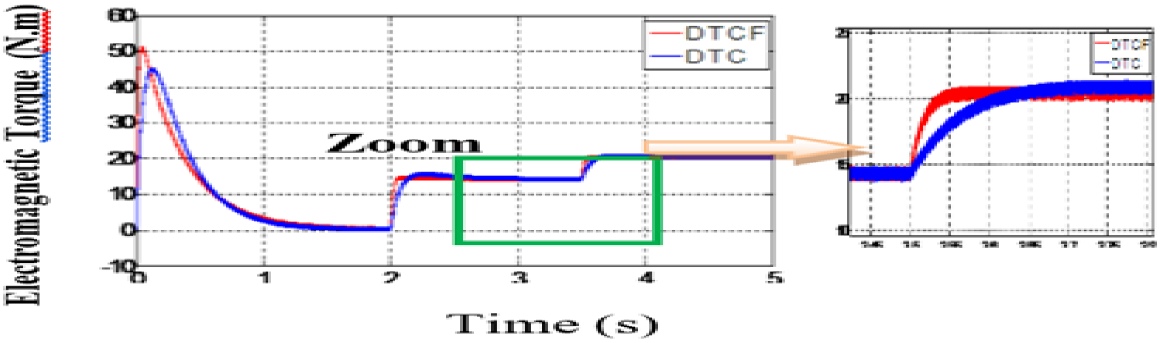

Fig. 12. Electromagnetic torque response of torque variation

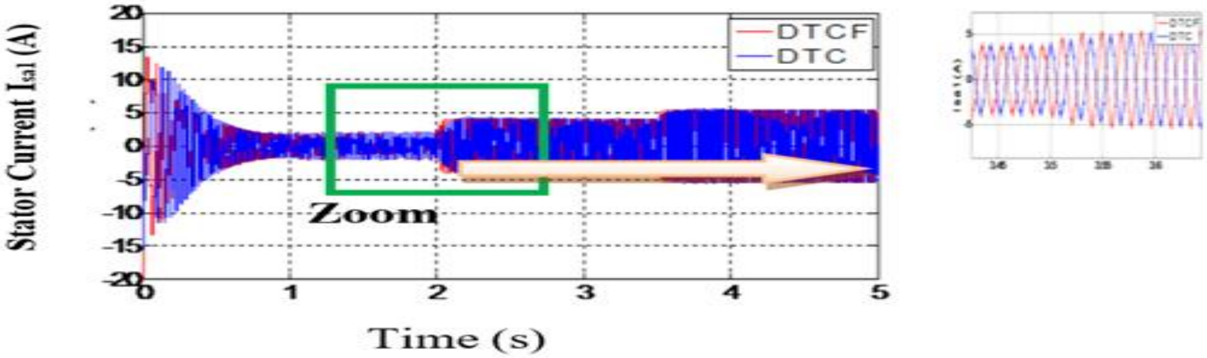

Fig. 13. Stator current of torque variation

2.3. Test for rotor resistance variation

The rotor resistance is sensitive to the temperature which changes gradually with respect to the load and the ambient temperature. In this test Fig. (14, 17,18). the value of the rotor resistance is augmented by 50% for the two controllers PI and FLC. These results confirm that the FLC controller demonstrates robustness under various operating conditions and shows a very satisfactory performance.

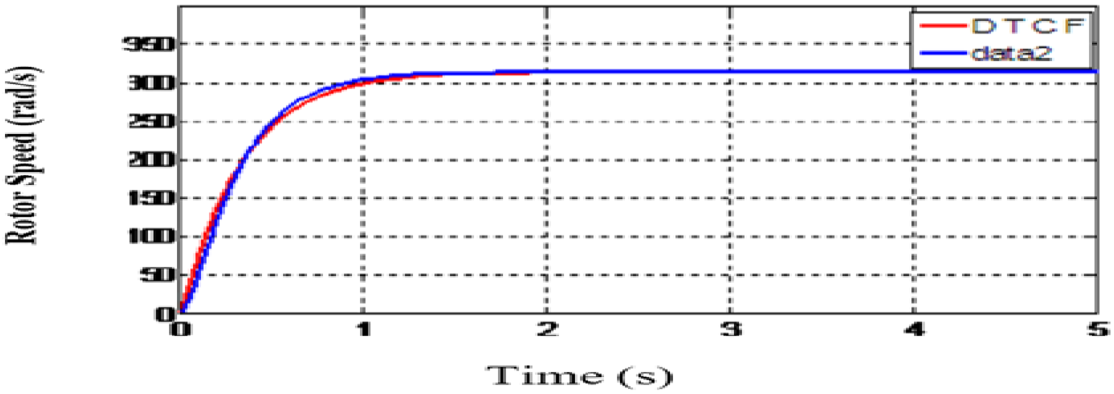

Fig. 14. Speed response for rotor resistance variation

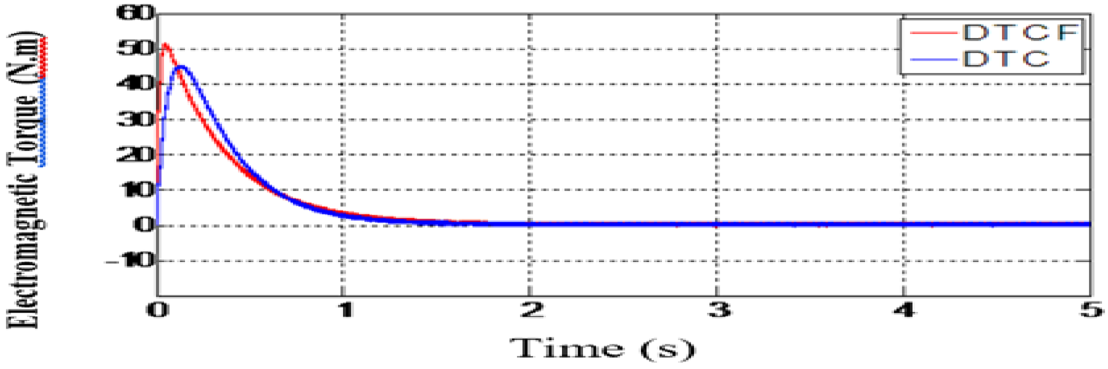

Fig. 15. Electromagnetic torque response for rotor resistance variation

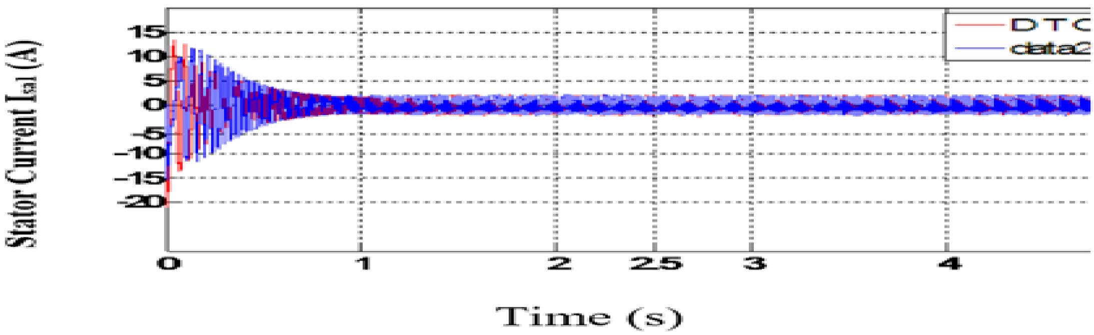

Fig. 16. Stator current response for rotor resistance variation

6. Conclusion

This paper presents a comparative study of direct torque of doubly star induction motor (DSIM) by using PI and fuzzy logic controller.

Based on the obtained results, in terms of speed reference tracking with the DSIM, the FLC gives a superior performance compared to the PI controller. The robustness tests show too that the FLC is more robust than the PI controller with the speed and torque and rotor resistance variations.

Consequently, the FLC controller is suitable for applications requiring a high tracking accuracy when external disturbances occur.

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8 APPENDIXE

The machine (DSIM) parameters are as follows:

Rated power: $P_{n=}$4.4Kw;
Pole pair: P=1;
Rated frequency: 50Hz;
Nominal speed: 3000rpm;
Resistance of the stator 1: R_{s1}=3.72Ω;
Resistance of the stator 2: R_{s2}=3.72Ω;
Resistance of the rotor: R_r= 2.12 Ω;
Inductance of the stator1: L_{s1}=0.022H;
Inductance of the stator2: L_{s2}=0.022H;
Inductance of the rotor: L_r=0.006H;
Mutual inductance: L_m=0.3672H;
Machine inertia: J=0.0625Kg.m^2;
Viscous coefficient: f=0.001Kg.m^2/s.