Direct torque control of doubly star induction machine fed by voltage source inverter using type-2 fuzzy logic speed controller

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ABSTRACT

This paper concerns the study of a direct torque control based on fuzzy logic type-2 for the speed regulation of a doubly star Induction Machine fed by voltage source inverter. This command has become one of the high performance control strategies for AC machine to supply a very rapid torque and flux control. The proposed technique consists to change the proportional and integral controllers by type-2 fuzzy logic controller. The performance of the scheme in different operating conditions is studied. Particular interest is given to the robustness of the fuzzy logic based control. Furthermore, the simulation results illustrate the efficiency and robustness of the type-2 fuzzy logic controller.

1. INTRODUCTION

The doubly star induction machine is demanded in aerospace applications and electric/hybrid vehicles, cement mills, rolling mills, mine hoists … etc (Zhao, 1995, Tir, 2016). Because this machine offers various advantages over conventional three-phase machines, such as minimize the amplitude and increasing the frequency of torque pulsation, minimize the current per phase, increasing the voltage per phase, reducing the rotor harmonic currents, and high reliability [1].

The control of the DSIM has progressed significantly in recent times; particularly with the direct torque control method was proposed in the middle of 1980 by I. Takahashi [5]. The DTC used the errors between the estimated and the reference values of flux nad torque in order to minimize the flux and torque errors within the band limits. This method is enabling us to directly control the inverter states [9].

Today, Fuzzy logic is a technique used in artificial intelligence and with widely used in different areas including: control, automation... etc. And the type-2 fuzzy logic has been attracting great research interests because are powerful tools and better able to handle uncertainties than their type-1 in complex processes [11, 14]. Does not need a detailed model [13]. Type-2 fuzzy logic controllers are one of useful control schemes to adjust the speed stabilization of DSIM. In this paper the type-2 fuzzy logic controller is developed and is investigated for a direct torque control of doubly star induction machine. For evaluates the performance index of the system as integral time-weighted absolute error (ITAE), integral absolute error (IAE), and integral squared error (ISE), for the proposed scheme (type-2 fuzzy logic controller) and is compared with the other controller i.e. the type-1 fuzzy logic.

This paper is structured as follows: In Section 2 the model of the DSIM is presented, and the model mathematical of VSI is presented in Section 3. Next, we will describe the direct torque control by a Type-2 fuzzy logic controller; the designed DTC models are introduced and explained, in order to improve the static and dynamic control performance of the DSIM in section 4 and 5. Section 6 shows simulation results for the performances of T2FLC speed controller of DTC-DSIM under various conditions operation. Finally, a general conclusion summary this work.

2. MATHEMATICAL MODEL OF DSIM

The double star induction machine represented by two stators windings: which are displaced by 30° electrical angle .and the rotor windings are sinusoidal distributed and have axes that are displaced apart by 120° [4].

The assumptions used for the model of this machine are the following: The magnetic saturation and core losses are neglected, Motor windings are sinusoidal distributed, and the two stars have same parameters, and the flux path is linear [6], the windings of the DSIM are shown in Figure. 1
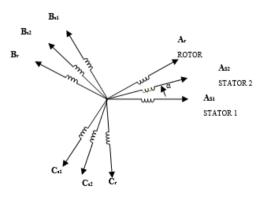

Figure 1. DSIM winding representation

The voltage equations of the DSIM have the following matrix form [7]:

$$[V_{s1,abc}] = [R_{s1}][i_{s1,abc}] + \frac{d}{dt}[\psi_{s1,abc}]$$

$$[V_{s2,abc}] = [R_{s2}][i_{s2,abc}] + \frac{d}{dt}[\psi_{s2,abc}]$$

$$0 = [R_r][i_{r,abc}] + \frac{d}{dt}[\psi_{r,abc}]$$

(1)

With

$V_{s1,abc}$, $V_{s2,abc}$: Stator voltages; $i_{s1,abc}$, $i_{s2,abc}$, $i_{r,abc}$: Stator and rotor currents;

$\psi_{s1,abc}$, $\psi_{s2,abc}$, $\psi_{r,abc}$: Stator and rotor flux; $[R_{s1}]$, $[R_{s2}]$, $[R_r]$: Resistance matrices stator and rotor .

To ensure the control, the DSIM model expressed in (α-β) axes presented by [3]:

$$\dot{X} = AX + BU$$

(2)

With,

$$X = [\psi_{s1\alpha}\,\psi_{s2\alpha} \quad \psi_{s1\beta} \quad \psi_{s2\beta} \quad \psi_{r\alpha} \quad \psi_{r\beta}]^T$$

$$U = [V_{s1\alpha}\,V_{s2\alpha} \quad V_{s1\beta} \quad V_{s2\beta} \quad 0 \quad 0]^T$$

$$I = [i_{s1\alpha}\,i_{s2\alpha} \quad i_{s1\beta} \quad i_{s2\beta} \quad i_{r\alpha} \quad i_{r\beta}]^T$$

where:

$V_{s1,\alpha\beta}$, $V_{s2,\alpha\beta}$: Stator voltages α-β components; $i_{s1,\alpha\beta}$, $i_{s2,\alpha\beta}$, $i_{r,\alpha\beta}$: Stator and Rotor currents α-β components; $\psi_{s1,\alpha\beta}$, $\psi_{s2,\alpha\beta}$, $\psi_{r,\alpha\beta}$: Stator and Rotor flux α-β components.

$$A = \begin{bmatrix} -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} & 0 \\ \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} & 0 \\ 0 & 0 & -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} \\ 0 & 0 & \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} \\ \frac{R_r L_a}{L_{s1}L_r} & \frac{R_r L_a}{L_{s2}L_r} & 0 & 0 & -\left(\frac{R_r}{L_r} - \frac{R_r L_a}{L_r^2}\right) & -\omega_r \\ 0 & 0 & \frac{R_r L_a}{L_{s1}L_r} & \frac{R_r L_a}{L_{s2}L_r} & \omega_r & -\left(\frac{R_r}{L_r} - \frac{R_r L_a}{L_r^2}\right) \end{bmatrix}$$

and

$$[A] = [A_{11}] + [A_{12}]\omega_r$$

$$[A_{12}] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$A_{11} = \begin{bmatrix} -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} & 0 \\ \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} & 0 \\ 0 & 0 & -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} \\ 0 & 0 & \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} \\ \frac{R_r L_a}{L_{s1}L_r} & \frac{R_r L_a}{L_{s2}L_r} & 0 & 0 & -\left(\frac{R_r}{L_r} - \frac{R_r L_a}{L_r^2}\right) & 0 \\ 0 & 0 & \frac{R_r L_a}{L_{s1}L_r} & \frac{R_r L_a}{L_{s2}L_r} & 0 & -\left(\frac{R_r}{L_r} - \frac{R_r L_a}{L_r^2}\right) \end{bmatrix}$$

The relations enter the flux and the current are [1]:

$$\begin{cases} \psi_{s1\alpha} = L_{s1}i_{s1\alpha} + L_m\left(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}\right) \\ \psi_{s1\beta} = L_{s1}i_{s1\beta} + L_m\left(i_{s1\beta} + i_{s2\beta} + i_{r\beta}\right) \\ \psi_{s2\alpha} = L_{s2}i_{s2\alpha} + L_m i\left(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}\right) \\ \psi_{s2\beta} = L_{s2}i_{s1\beta} + L_m\left(i_{s1\beta} + i_{s2\beta} + i_{r\beta}\right) \\ \psi_{r\alpha} = L_r i_{r\alpha} + L_m\left(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}\right) \\ \psi_{r\beta} = L_r i_{r\beta} + L_m\left(i_{s1\beta} + i_{s2\beta} + i_{r\beta}\right) \end{cases}$$

(3)

where:

L_m: Cyclic mutual inductance between stator 1, stator 2 and rotor; $L_{s1, s2, r}$: the inductance of a stator 1, stator 2 and rotor respectively; $L_{s1}+L_m$, $L_{s2}+L_m$, L_r+L_m: the total inductance of a stator 1, stator 2 and rotor respectively.

The electromagnetic torque and the mechanical equations can be written as:

$$T_{em} = p\frac{L_m}{L_m + L_r}(\psi_{r\alpha}(i_{s1\beta} + i_{s2\beta}) - \psi_{r\beta}(i_{s1\alpha} + i_{s2\alpha}))$$

(4)

$$J\frac{d\Omega}{dt} = T_{em} - T_r - K_f\Omega$$

(5)

3. VOLTAGE SOURCE INVERTER

The voltage source inverter (VSI) is a static converter constituted by switching cells generally with IGBT for high powers. The operating principle can be expressed by imposing on the machine the voltages with variable amplitude and frequency starting from a standard network.

The mathematical model of VSI presented by:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

(6)

4. DIRECT TORQUE CONTROL

The objective of direct torque control is a based on the switching tables with hysteresis of torque and stator flux. The reference values of flux (ψ_s) and torque (T_{em}) are compared to their actual values and the resultant errors are fed into a two level hysteresis comparator for the flux and three level hysteresis comparator for the torque, who allows controlling

the motor in the two directions of rotation (figure.2). Using this method, for the minimization of the commutations of the inverter switches, on the torque/stator flux decoupling, on the control of the PWM generator. This particularity defines the DTC as an adapted control technique of AC machines [9, 16].
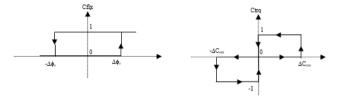

Figure 2. Hysteresis comparator, (a): two level hysteresis comparator for the flux, (b): three level hysteresis comparator for the torque

The principle of direct torque control operation explained by analyzing the stator voltage equation in the stator flux reference frame [16]:

$$\psi_{s1\alpha est} = \int_0^{T_e} \left(V_{s1\alpha} - R_{s1} i_{s1\alpha} \right) dt + \psi_{s0} \tag{7}$$

$$\psi_{s1\beta est} = \int_0^{T_e} \left(V_{s1\beta} - R_{s1} i_{s1\beta} \right) dt + \psi_{s0} \tag{8}$$

$$\psi_{s2\alpha est} = \int_0^{T_e} \left(V_{s2\alpha} - R_{s1} i_{s2\alpha} \right) dt + \psi_{s0} \tag{9}$$

$$\psi_{s2\beta est} = \int_0^{T_e} \left(V_{s2\beta} - R_{s1} i_{s2\beta} \right) dt + \psi_{s0} \tag{10}$$

During the switching interval [0-Te], $V_s >> R_s i_s$ we can express:

$$\psi_s(t) = \psi_{s0} + V_s T_e \tag{11}$$

The selected of the voltage vector will be applied to the DSIM at the end of the sample time, as are exposed in (11). by neglecting the stator resistances equation (11) implies that the ends of the stator flux vectors will moves in the direction of the applied voltage vectors as shown in this figure.
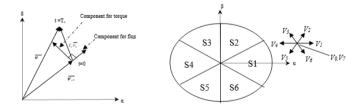

Figure 3. (a): Stator flux vector deviation, (b): Voltage vector selection

4.1 Stator flux estimation

The magnitude of stator flux, which can be estimated as following [16]:

$$\overline{\psi_{sest}} = \int_0^{T_e} \left(\overline{V_s} - R_s \overline{i_s} \right) dt \tag{12}$$

The stator flux linkage phases are given by:

$$\left| \psi_{s1est} \right| = \sqrt{\psi_{s1\alpha est}^2 + \psi_{s1\beta est}^2} \tag{13}$$

$$\left| \psi_{s2est} \right| = \sqrt{\psi_{s2\alpha est}^2 + \psi_{s2\beta est}^2} \tag{14}$$

The stator flux linkage phase's positions are:

$$\theta_{s1est} = arctg\left(\frac{\psi_{s1\beta est}}{\psi_{s1\alpha est}} \right) \tag{15}$$

$$\theta_{s2est} = arctg\left(\frac{\psi_{s2\beta est}}{\psi_{s2\alpha est}} \right) \tag{16}$$

The electromagnetic torque expressions are given by:

$$T_{em1est} = p\left(\psi_{s1\alpha est} i_{s1\beta} - \psi_{s1\beta est} i_{s1\alpha} \right) \tag{17}$$

$$T_{em2est} = p\left(\psi_{s2\alpha est} i_{s2\beta} - \psi_{s2\beta est} i_{s2\alpha} \right) \tag{18}$$

$$T_{emest} = \Gamma_{em1est} + \Gamma_{em2est}$$

$$T_{emest} = p\left(\begin{array}{c} \left(\psi_{s1\alpha est} i_{s1\beta} - \psi_{s1\beta est} i_{s1\alpha} \right) \\ + \left(\psi_{s2\alpha est} i_{s2\beta} - \psi_{s2\beta est} i_{s2\alpha} \right) \end{array} \right) \tag{19}$$

4.2 Elaboration of the switching table

For the selection of the switching state of the inverter used a switching table based on the hysteresis comparators (Cflx, Ctrq) and the sector where is the stator vector flux (ψ_s) in the plan (α-β), in order to maintain the magnitude of electromagnetic torque and stator flux interior the hysteresis bands [9].

Table 1. Switching table with zero voltage vectors

Sectors		1	2	3	4	5	6
Cflx=1	Ctrq= 1	V_2	V_3	V_4	V_5	V_6	V_1
	Ctrq =0	V_7	V_0	V_7	V_0	V_7	V_0
	Ctrq = -1	V_6	V_1	V_2	V_3	V_4	V_5
Cflx=0	Ctrq = 1	V_3	V_4	V_5	V_6	V_1	V_2
	Ctrq =0	V_0	V_7	V_0	V_7	V_0	V_7
	Ctrq = -1	V_5	V_6	V_1	V_2	V_3	V_4

where: $V_0(000)$, $V_7(111)$, $V_1(100)$, $V_2(110)$, $V_3(010)$, $V_4(011)$, $V_5(001)$, $V_6(101)$.

Table 1 shows the sequences corresponding to each position, which selects the optimal switching state S_a, S_b, S_c.

For example:

- if stator flux lies in sector 1, Ctrq is positive and Cflx is Positive then the motor has to accelerate to reduce the art quickly vector V_2 is applied which rotates the flux in clockwise direction.
- If stator flux lies in sector 1, Ctrq is negative and Cflx is positive, then the motor has to decelerate vector V_6 is applied which rotates the flux in anti - clockwise direction.

5. TYPE-2 FUZZY LOGIC CONTROLLERS

Type-2 fuzzy sets are more difficult to use compared that type-1 fuzzy sets, the fuzzy inference system (FIS) is a rule-based system that uses fuzzy logic instead of Boolean logic. Type-2 fuzzy set let us to model and to minimize the effects of uncertainties in rule of the system fuzzy logic. Its basic structure has four components (figure 4) [17, 18].
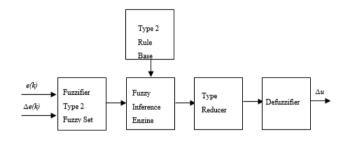
Figure 4. Components of PI Type-2 FLC

The inputs of the T2FLC are the error rotor speed and its variation.

$$e(k) = \omega_{ref}(k) - \omega_r(k) \tag{20}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{21}$$

Figure 5 show the structure of a control based on type-2 fuzzy logic [17]:
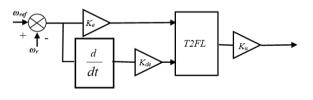
Figure 5. Bloc diagram of T2FLC

Fuzzy logic type-2 system includes 4 components [17].

5.1 Fuzzification

Convert classical data or crisp data (e and de) into fuzzy data or Membership Functions (MFs) such as NB (Negative Big), N (Negative), Z (Zero), P (Positive) and PB (Positive Big) shows in figure 6 [17]:
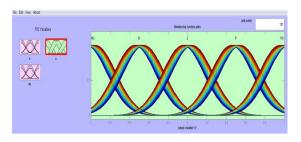

Figure 6. The Type-2 fuzzy membership functions of error speed *e* and change in error speed *de* and output variable u

5.2 Fuzzy inference engine

One need combines the Membership Functions with the control rules to derive the control output, and arrange those outputs into a table called the lookup table. The control rule is the core of the fuzzy inference process, and those rules are directly related to a human being's intuition and feeling [18].

Rule 1: if e is NB, and de is NB, then U is NB.
Rule 2: if e is NB, and de is N, then U is NB.
Rule 25: if e is PB, and de is PB, then U is PB.
The rule base is as listed in table 2.

Table 2. Rule base of type 2 fuzzy logic

Δu		e			
	NB	N	Z	P	PB
NB	NB	NB	N	N	Z
N	NB	N	N	Z	PB
Δe Z	N	N	Z	P	PB
P	N	Z	P	P	PB
PB	Z	P	P	PB	PB

5.3 Type reducer

The type-reducer generates a type-1 fuzzy set output, which is then converted in a numeric output through running the defuzzifier. This type-1 fuzzy set is also an interval set, for the case of our fuzzy logic system we used center of sets (cos) type reduction, $y_{cos}(x)$, which is expressed as [14]:

$$y_{cos}(x) = [y_u, y_l] \tag{22}$$

$$y_u(x) = \frac{\sum_{i=1}^{M} f_u^i y_u^i}{\sum_{i=1}^{M} f_u^i} \tag{23}$$

$$y_l(x) = \frac{\sum_{i=1}^{M} f_l^i y_l^i}{\sum_{i=1}^{M} f_l^i} \tag{24}$$

where:
f_u^i, f_l^i: area of i_{th} high and inferior output membership function,
y_u^i, y_l^i: centroid of i_{th} high and inferior output membership function.

5.4 Defuzzification

From the type-reducer, we obtain an interval set y_{cos}, to defuzzify it we use the average of y_l and y_r, so the defuzzified output of an interval singleton type-2 fuzzy logic system is [13]:

$$y(x) = \frac{y_u(x) + y_l(x)}{2} \tag{25}$$

The block diagram of the fuzzy logic type-2 for the DTC approach of the DSIM is shown in figure 7.
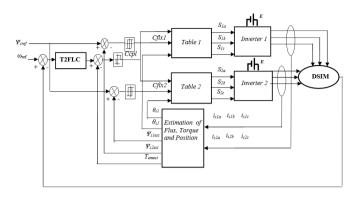

Figure 7. Schema global of DTC using T2FLC for DSIM

6. RESULTS AND DISCUSSION

The proposed scheme has been implemented with Matlab/ Simulink in order to evaluate its performance. The parameters of the DSIM are summarized in Appendix. The robustness of the Direct Torque Control using T2FLC of the DSIM is visualized for two tests: the first is the load torque variation; the second is the change of speed and load torque variation.

6.1 Load torquze variation

In first test the Torque variation with the sign of resistant torque T_r = 14 N.m for the period of the interval (1.5-3) s, and the DSIM runs with speed values 150 rad/s.
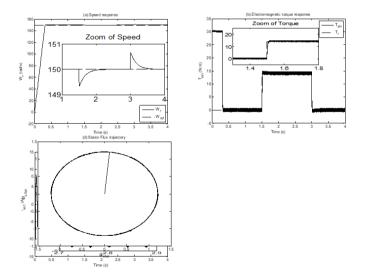

Figure 8. Speed, torque, current stator and park trajectory characteristic of direct torque control with T2FLC Controller, at variation in load torque

The speed reaches its reference value (150 rad/s) after (0.4s) without overtaking. At t=(1.5-3)s, we applied a load torque (14 N.m), the stator current increase (4.3A) and the machine developed an electromagnetic torque for compensate the load

torque, it reaches at starting (30 N.m). The excellent dynamic performance of stator field is evident.

6.2 Robustness test

In next test the load torque is applied at (1-1.5) s T_r = 7N.m, (2.5-4) s T_r = 14N.m, and the DSIM runs with speed variation values [150rad/s during (0-1) s, 100 rad/s for the duration of (1-2.5) s and
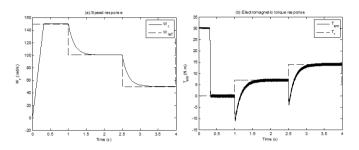50rad/s at (2.5-4) s].

Figure 9. Speed, Electromagnetic torque characteristic of direct torque control with T2FLC Controller, at changes in Speed and load torque variation

Figure 9. illustrate the change in command speed and the load torque is realized. The rotor speed obtained by the T2FLC track very quickly the desired reference speed and the motor output torque will increase to cover this load Figure 9 (a), (b). This test has for object the study of controller behaviors in pursuit and in regulation.

6.3 Performances evaluate

For judge the performance of the controllers utilized *ITAE*, *IAE* and *ISE* criterion is widely adopted to evaluate the dynamic performance of the control system.
The index *ITAE, IAE* and *ISE* is expressed as follows [8]:

$$ITAE = \int_0^T t|e(t)|dt \tag{26}$$

$$IAE = \int_0^T |e(t)|dt \tag{27}$$

$$ISE = \int_0^T e^2(t)dt \tag{28}$$

Table 3. Quantitative comparison between the proposed FLC controllers

		DTC-T1FLC (Hellali, 2018)	DTC-T2FLC
	ITAE	3.232	2.526
First Test	*IAE*	26.31	23.96
	ISE	2596	2423
	ITAE	34.20	34.06
Second	*IAE*	42.64	40.45
Test	*ISE*	3052	2841

ITAE: integral time-weighted absolute error; *IAE*: Integral

absolute error; *ISE*: integral squared error.

For quantitative comparison between two regulators, *ITAE, IAE* and *ISE* are used as the criterion. Table.3 shows the *ITAE, IAE* and *ISE* values of direct torque control using two regulators (T1FLC and T2FLC).

This comparison shows clearly that the T2FLC gives good performances and it's more robust than T1FLC.

7. CONCLUSION

In this paper, we presented control the doubly star induction machine by direct torque control using a type-2 fuzzy logic regulator. We established a mathematical model of the machine to study static behavior and dynamic of this machine.

The complete dynamic model of the Direct Torque Control system is developed and simulated by using MATLAB-SIMULINK. Then, we have continued to improve the direct torque control by the application of type-2 fuzzy logic. The simulation results show that the DTC-T2FLC present a good dynamics performance and his robustness with speed and load torque variation.

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Appendix

Table 4. Machine parameters [7]

DSIM Mechanical Power	4.5 kW	Stators 1,2 self inductances	0.022 H
Nominal voltage	220 V	Rotor inductance	0.006 H
Frequency	50 Hz	Mutual inductance	0.3672 H
Pole pair number	1	Moment of inertia	$0.0625 Nms^2/rad$
Stators 1,2 resistances	3.72 Ω	Friction coefficient	0.001Nms/rad
Rotor resistance	2.12 Ω		

List of abbreviations and symbols

Abbreviations	Designation
DSIM	Doubly Star Induction Motor
DTC	Direct Torque Control
T2FLC	Type-2 Fuzzy Logic Controller
T1FLC	Type-1 Fuzzy Logic Controller
VSI	Voltage Source Inverter
Ω_r	the rotor angular speed
T_{em}	Electromagnetic torque
K_f	Friction coefficient
J	Moment of inertia
P	Number of pole pairs
T_r	Load torque