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Direct Torque Control for Induction Motor with broken bars using Fuzzy Logic Type-2

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Abstract: This paper introduces the design of a fuzzy logic controller in conjunction with direct torque control strategy for induction motor machine. Fuzzy logic control is used to combine both methods to obtain a compromise which reduces the sensitivity to the variation of the electrical parameters (broken bars) at each operating point. The controller is designed according to fuzzy logic rules, such that the system is fundamentally robust. To test the fuzzy control strategy a simulation platform using MATLAB/SIMULINK was built which includes induction motor d-q model, inverter model, fuzzy logic switching table and the stator flux and torque estimator. The simulation results verified the new control strategy.

Keywords: Induction motor, DTC, type -2 Fuzzy logic, FL2DTC, Rotor fault.

1. Introduction

Advanced control of electrical machines requires an independent control of magnetic flux and torque. For that reason it was not surprising, that the DC-machine played an important role in the early days of high performance electrical drive systems, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively. The introduction of Field Oriented Control (Lascu, 2000) meant a huge turn in the field of electrical drives, since with this type of control the robust induction machine can be controlled with a high performance. Later in the eighties a new control method for induction machines was introduced (Vasudevan, 2005 and Lin 2007). The Direct Torque Control (DTC) method is characterized by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e.

a modulation technique for the inverter is not needed. However if the control is implemented on a implemented on a digital system (which can be considered as a standard nowadays); the actual values of flux and torque could cross their boundaries too far (Grawbowski, 2000), which is based on an independent hysteresis control of flux and torque. The main advantages of DTC are absence of coordinate transformation and cu Induction motor is widely used in industry because of its reliability and low cost. However, since the dynamical model of induction motor is strongly nonlinear, the control of induction motor is a challenging problem and has attracted much attention. Many controllers have been developed. We can cite as follows.

FL was introduced by Zadeh in the 1960’s. FL is a superset of conventional (Boolean) logic that has been extended to process data by allowing partial set membership rather than crisp set membership or non-membership. FL is a problem-solving control system methodology. FL provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information.

Type-2 FLS have been developed that satisfy the following fundamental design requirement (Mendel, 2001). When all sources of uncertainty disappear, a type-2 FLS must reduce to a comparable type-1 FLS Takagi-Sugeno-Kang type fuzzy model structure, also being referred to as TSK fuzzy logic systems (FLS) (Takagi & Sugeno, 1985), after Takagi, Sugeno & Kang, was proposed in an effort to develop a systematic approach to generating fuzzy rules from a given input-output data set. This model consists of rules with fuzzy antecedents and mathematical function in the consequent part. Usually, conclusion function is in form of dynamic linear equation. The antecedents divide the input space into a set of fuzzy regions, while consequents describe behaviours of the system in those regions.

2. Direct Torque Control with Three-Level Inverter

The basic functional blocks used to implement the DTC scheme are represented in Figure 1. The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator (Grawbowski, 2000). Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration (Vasudevan, 2005).

The voltage expressions of the machine used in the stator referential is given as:

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + \dfrac{d\overline{\Phi}_s}{dt} \\ \overline{V}_r = \overline{0} = R_r \overline{I}_r + \dfrac{d\overline{\Phi}_r}{dt} - jw\overline{\Phi}_r \end{cases} \tag{1}$$

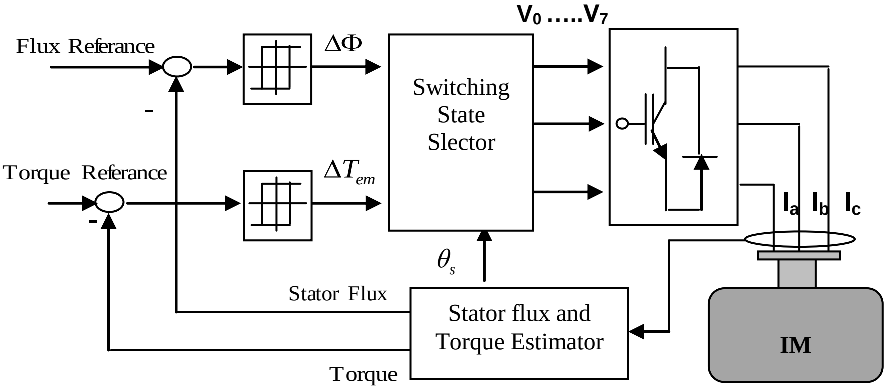

Figure 1. Basic configuration of DTC scheme

2.1. Vector model of inverter output voltage

In a voltage fed three phases, the switching commands of each inverter leg are complementary. So for each leg a logic state Si (C_1, C_2, C_3) can be defined. Si is **1** if the upper switch is commanded to be closed and **0** if the lower one in commanded to be close (first) (Lee, 2002).

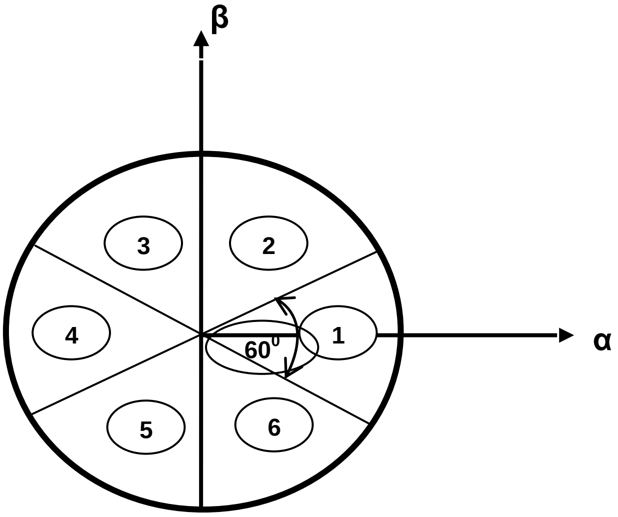

Figure 2. Partition of the α β plane into 6 angular sectors

Since there are 3 independent legs there will be eight different states, so 8 different voltages. Applying the vector transformation described as:

$$V_s = V_{s\alpha} + jV_{s\beta} = \sqrt{\frac{2}{3}}\left[V_{aN} + V_{bN}e^{\left(j\frac{2\Pi}{3}\right)} + V_{cN}e^{\left(j\frac{4\Pi}{3}\right)}\right] \tag{2}$$

2.2. Stator flux control

The components of the current ($I_{s\alpha}$, $I_{s\beta}$), and stator voltage ($V_{s\alpha}$, $V_{s\beta}$) are obtained by the application of the transformation given by (3) and (4), (Lee, 2002 and Vasudevan, 2005).

$$\begin{cases} I_{s\alpha} = \sqrt{\frac{3}{2}} I_{sa} \\ I_{s\beta} = \frac{1}{\sqrt{2}}\left(I_{sb} - I_{sc}\right) \end{cases} \tag{3}$$

$$\begin{cases} V_{s\alpha} = \sqrt{\frac{3}{2}} U_0\left[C_1 - \frac{1}{2}\left(C_2 + C_3\right)\right] \\ V_{s\beta} = \frac{1}{\sqrt{2}} U_0\left(C_2 - C_3\right) \end{cases} \tag{4}$$

The components of the stator flux ($\phi_{s\alpha}$, $\phi_{s\beta}$) given by (5).

$$\begin{cases} \phi_{s\alpha}(t) = \int_0^t (V_{s\alpha} - R_s i_{s\alpha})dt \\ \phi_{s\beta}(t) = \int_0^t (V_{s\beta} - R_s i_{s\beta})dt \end{cases} \tag{5}$$

The electromagnetic couple be obtained starting from the estimated sizes of flux ($\phi_{s\alpha}$,$\phi_{s\beta}$□ and calculated sizes of the current, $I_{s\alpha}$□$I_{s\beta}$□).

$$T_{em} = p(\Phi_{s\alpha} I_{s\beta} - .\Phi_{s\beta}\, I_{s\alpha}\ ) \tag{6}$$

The stator resistance can be assumed constant during a large number of converter switching periods Te. The voltage vector applied to the induction motor remains also constant during one period Te. The stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance as given by equations (7):

$$\Phi_s(t) = \int \left(V_s - R_s I_s\right)dt \tag{7}$$

During the switching interval, each voltage vector is constant and (7) is then rewritten as in (8):

$$\Phi_s(t)=\Phi_{s0}+V_sT_e \tag{8}$$

The angle of flux linkage θ_s an angle between stator's flux and a reference axis is defined by equation (9):

$$\theta_s=\arctan\frac{\Phi_{\beta s}}{\Phi_{\alpha s}} \tag{9}$$

3. Fuzzy Logic Direct Torque Control of Induction Motor

In DTC induction motor drive, there are torque and flux ripples because none of the inverter states is able to generate the exact voltage value required to make zero both the torque electromagnetic error and the stator flux error (Belhamdi, 2013 and Saravana, 2009). The suggested technique is based on applying switching state to the inverter and the selected active state just enough time to achieve the torque and flux references values. A null state is selected for the remaining switching period, which won't almost change both the torque and the flux. Therefore, the switching state has to be determined based on the values of torque error, flux error and stator flux angle. Exact value of stator flux angle (θ_s) determines where stator flux lies (Lee, 2002 and Ashok, 2009).

3.1. Type-2 Fuzzy Logic

A type-2 fuzzy set is characterized by a fuzzy membership function, where the membership value or grade for each element of this set is a fuzzy set in the interval [0, 1]; unlike a type-1 fuzzy set where the membership grade is a crisp value. As such, the membership functions of type-2 fuzzy sets are three dimensional functions, with what is known as the set's footprint of uncertainty (FOU) representing the third dimension. In fact, it is this FOU that provide type-2 FLSs with additional degrees of freedom and make it possible for them to directly model and handle more types of uncertainties with higher magnitudes than their type-1 counterparts. Moreover, using type-2 fuzzy sets to represent a certain system's inputs and outputs can result in a smaller rule base as when a type-1 FLS was used. A block diagram of a typical type-2 FLS is depicted in Figure. 2. It is generally composed of five components: a fuzzifier, a rule base, a fuzzy inference engine, a type-reducer and a defuzzifier. In essence, it has a very similar structure to a type-1 FLS (Wu, 2004 and Mendel, 2007).

Type-2 fuzzy sets are generalized forms of those of type 1 (with the FOU as an additional degree of freedom). Mathematically, a type-2 fuzzy set, denoted as $\tilde{A}$, is characterized by a type-2 membership function $\mu_{\tilde{A}}(x,u)$, where $x \in X$ and $u \in J_x \subseteq [0,1]$

$$\tilde{A} = \{((x,u), \mu_{\tilde{A}}(x,u)| \quad \forall x \in X, \quad \forall u \in J_x \subseteq [0,1])\} \tag{10}$$

In which $0 \le \mu_{\tilde{A}}(x,u) \ge 1$.For a continuous universe of discourse, $\tilde{A}$ can be expressed as

$$\tilde{A} = \int_{x\in X} \int_{u\in J_x} \frac{\mu_{\tilde{A}}(x,u)}{(x,u)} \qquad J_x \subseteq [0,1] \ \} \tag{11}$$

Where J_x is referred to as the primary membership of **x**. As in type-1 fuzzy logic, discrete fuzzy sets are represented by the symbol $\sum$ instead of $\int$. The secondary membership function associated to $x = x'$, for a given $x' \in X$, is the type-1 membership function defined by $\mu_{\tilde{A}}(x = x', u), \quad \forall u \in J_x$ (Qureshi,2009 and Mendel, 2007).

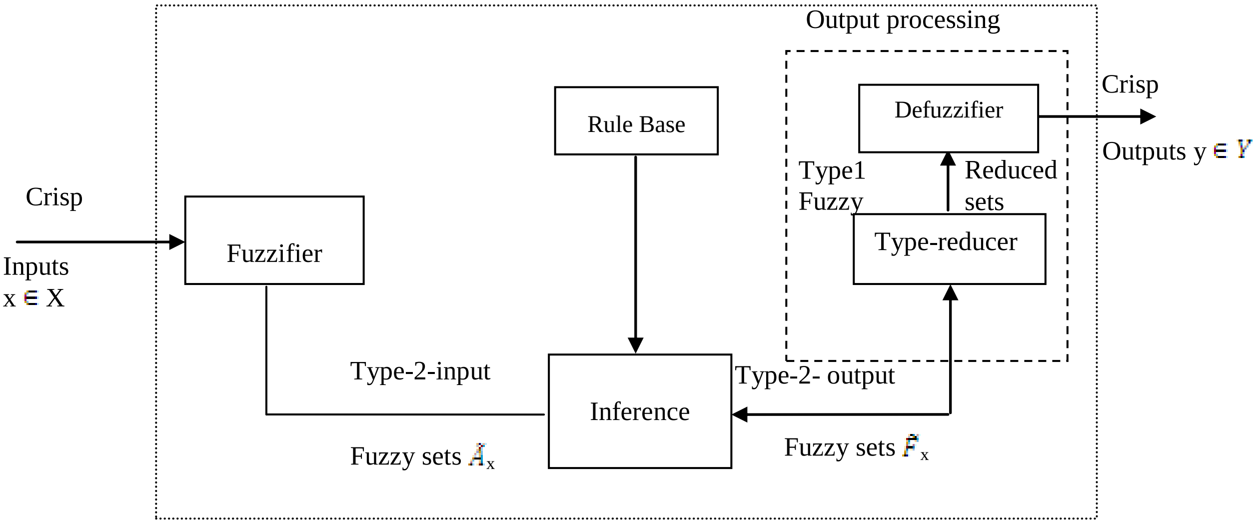

Figure 3. Block diagram of a type-2 FLS

The uncertainty in the primary membership of a type-2 fuzzy set $\tilde{A}$ is represented by the FOU and is illustrated in Figure.4. Note that the FOU is also the union of all primary memberships.

$$FOU(\tilde{A}) = \bigcup_{x\in X}$$

The upper and lower membership functions, denoted by $\overline{\mu}_{\tilde{A}}(x)$and $\underline{\mu}_{\tilde{A}}(x)$, respectively, are two type-1 membership functions that represent the upper and lower bounds for the footprint of uncertainty of an interval type-2 membership function $\mu_{\tilde{A}}(x,u)$, respectively FLS (Mendel, 2007). Membership function in interval type-2 fuzzy logic set as an area called Footprint of Uncertainty (FOU) which is limited by two type1 membership function. Those are: Upper membership Function (UMF) and Lower Membership function (LMF).

Interval type-2 membership function is shown in figure 4.

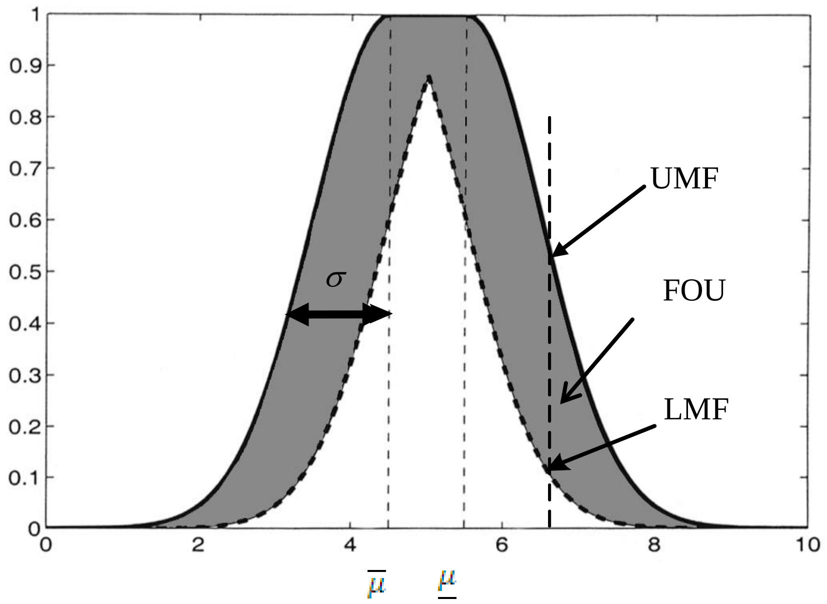

Figure.4. Interval type-2 fuzzy set with adjustable uncertain mean and adjustable standard deviation.

Fuzzy logic type-2 system includes 4 components (Mendel, 2007):

- **Fuzzifier:** Translates inputs (real values) to fuzzy values.
- **Inference System:** Applies a fuzzy reasoning mechanism to obtain a fuzzy output.
- **Type Defuzzifier/Reducer:** The defuzzifier translates one output to precise values; the type reducer transforms a Type-2 Fuzzy Set into a Type-1 Fuzzy Set.
- **Knowledge Base:** Contains a set of fuzzy rules, and a membership functions set known as the database.

- **Rule Control**

It is assumed that the input data of the type-2 fuzzy system is $x_1 \in X_1$, $x_2 \in X_2$,………and $x_p \in X_p$, and fuzzy output sets is $y \in Y$. The rules of the type-2 fuzzy system are denoted as follows: R^i: IF x_1 is $\tilde{F}_1^i$ and x_2 is $\tilde{F}_2^i$ ....and x_p is $\tilde{F}_p^i$ then y is $\tilde{G}^i$

Where $\tilde{F}_j^i = \left[\underline{\mu}_{\bar{A}}(x), \overline{\mu}_{\bar{A}}(x) \right]$ denotes the jth antecedent of rule i and $\tilde{G}^i$ indicates the consequent of rule i.

The expert's experience is incorporated into a knowledge base with 25 rules (5 x 5). This experience is synthesized by the choice of the input-output (I/O) membership functions and the rule base. Then, in the second stage of the FLC, the inference engine, based on the input fuzzy variables e and Δe, uses appropriate IF-THEN rules in the knowledge base to imply the rules in the knowledge base to imply the final output fuzzy sets as shown in the Table1, where NB, N, Z, P, PB, correspond to Negative Big, Negative, Zero, Positive, Positive Big respectively (Belhamdi, 2013).

		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

Table1. Fuzzy rule for type-2 FLCs

4. Simulation Results

4.1. Healthy Case

Direct torque control of induction motor using fuzzy logic was also simulated using the MATLAB / SIMULINK package. Membership functions were chosen and simulations were carried out, the sampling time taken for simulation 4 s. Torque and flux reference values taken were 3.5 N.m and 1.1 Wb. Figure (5) show the evolution the speed of the electromagnetic torque, and stator current. Fine With of the mode of starting (0.2s). We observe that the control system reaches its steady state by showing good performance and great stability for the two approaches.

The flux and torque stabilize around their reference values. The simulation results show that flux and torque responses are very good dynamic torque response for FLDTC2.

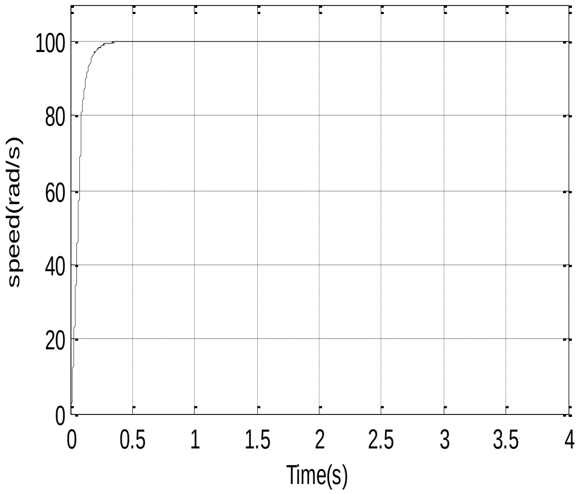

Fig. 5.a: Speed response

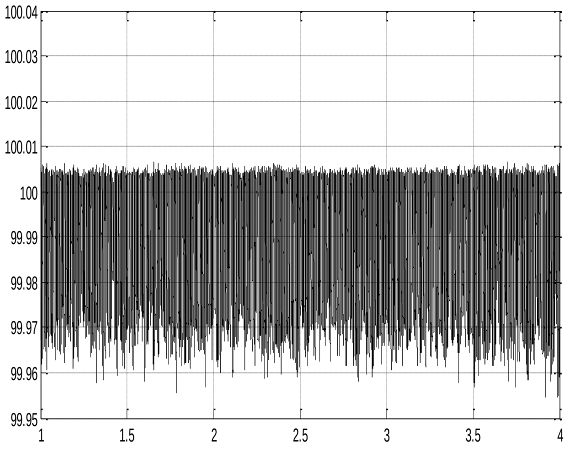

Fig. 5.b: Zoom of speed response

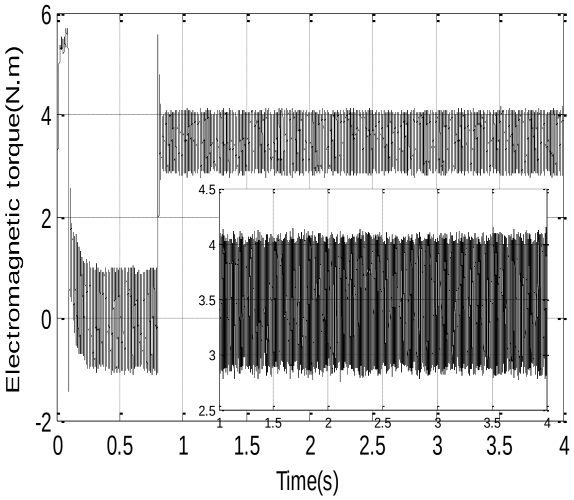

Fig. 5.c: Torque for healthy motor

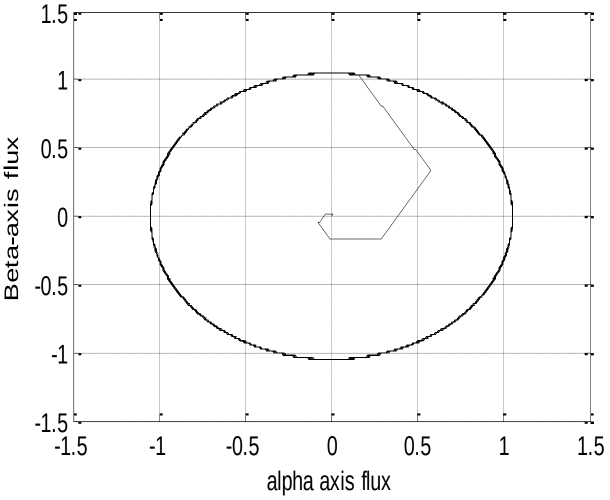

Fig. 5.d: The stator flux circle

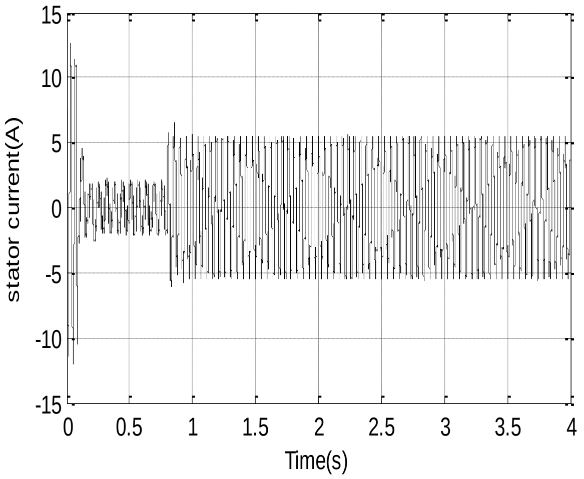

Fig. 5.e: The Stator current

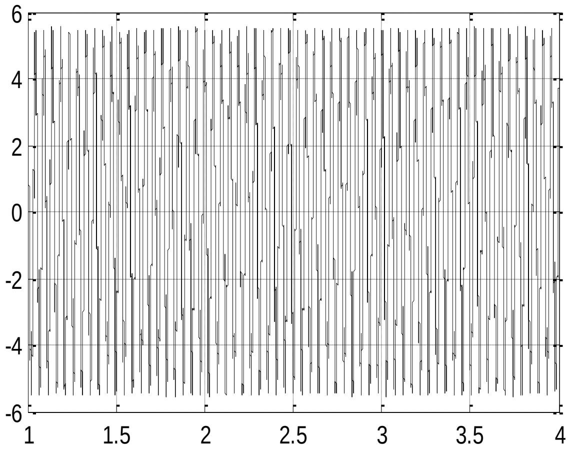

Fig. 5.f: Zoom of stator current

Figure. 5. Simulation results without Small-scale model

4.2. Case of two broken bars

In the simulation tests a simplified mathematical model of the induction motor with broken rotor bars was used .The each rotor fault was modeled as a full broken rotor bar. All simulation tests were performed in per unit values .The squirrel-cage rotor of the tested IM consists of 16 bars .The reference speed is set to 100 rad/s (**fig. 6. a**). Then a load torque is applied at t=0.8s.When the machine is healthy and when torque is required, symmetrical rotor-bar currents appear with pulsation the slip frequency. At t=2s, we simulate a first bar is broken this is achieved by increasing its resistance. We also note that the broken bar has no influence on the dynamic responses of torque, speed, flux, and stator current. The second bar is broken a t=3s. We notice the appearance of fluctuations on the shapes of the torque. Speed remains always not very disturbed by this defect. For current I have one sees well a deformation during the rupture of the bar. We can note that the broken bar does not affect the stability of system response. From this analysis, the torque and flux present a high dynamic performances and good precision in steady state. It can be observed that the torque and flux are decoupled.

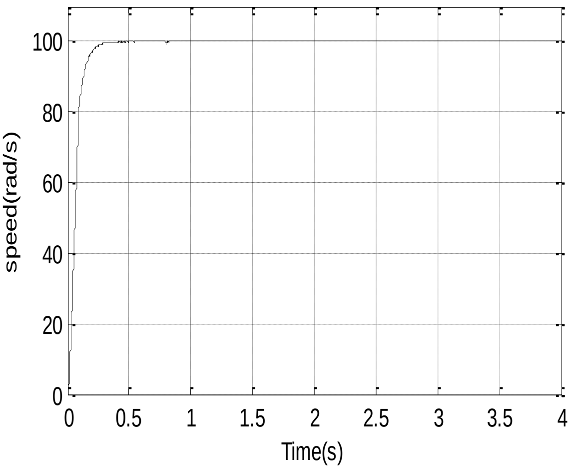

Fig. 6.a: Speed response

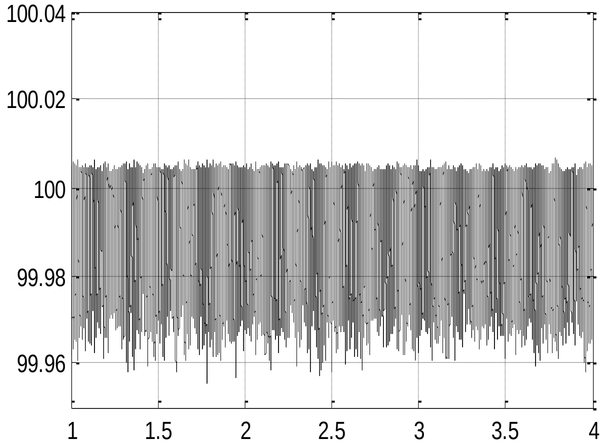

Fig. 6.b: Zoom of speed response

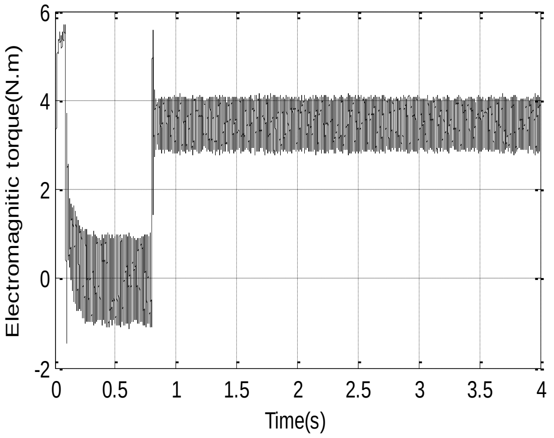

Fig. 6.c: Torque for healthy motor and broken bar No 1 and 2

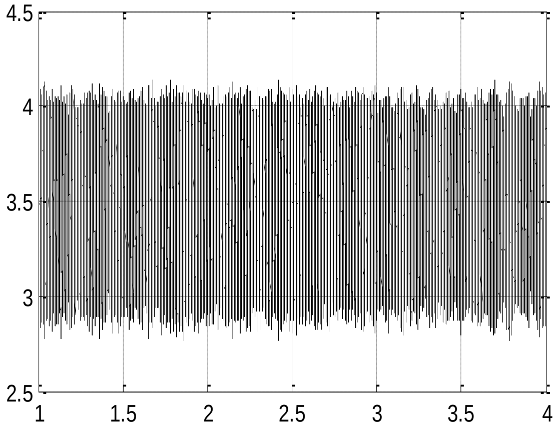

Fig. 6.d: Zoom for the torque

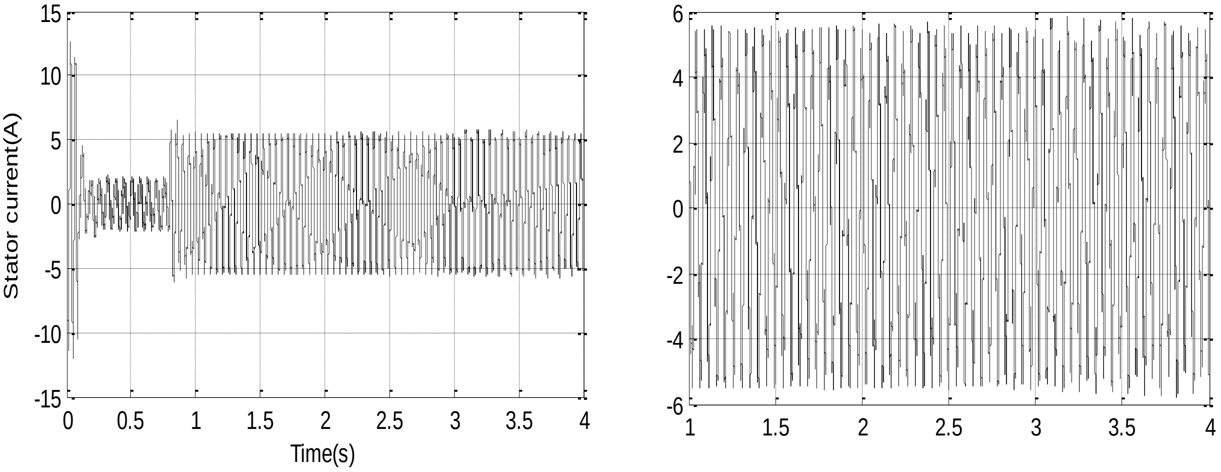

Fig. 6.e: The Stator current

Fig.6.f: Zoom of stator current

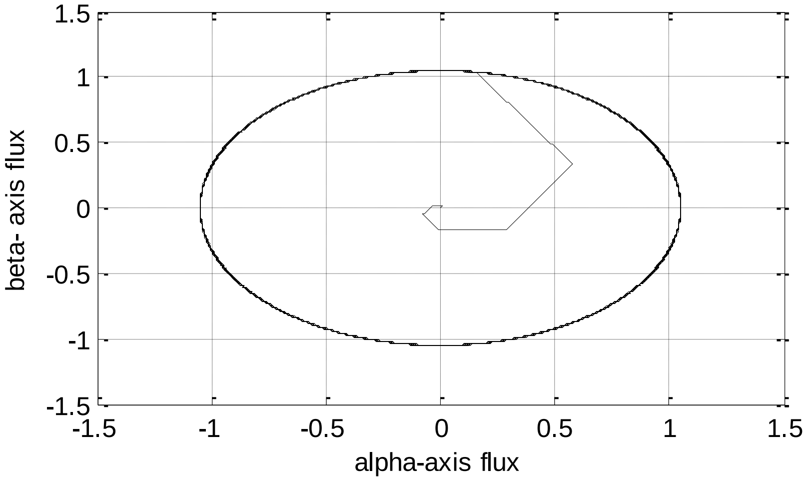

Fig. 6.g: The stator flux circle

Figure. 6. Simulation results without rotor defects

5. Conclusion

The main objective of this research was an analysis of the fault rotor influence on the FLDTC2 control signals and determining the visible absence of a signature in the selected control signals. Simulation results show that FLDTC2 asynchronous machine can achieve precise control of the stator flux and torque. Fuzzy Logic Direct Torque Control Type-2 an induction machine provides a satisfactory solution to the problems of robustness and dynamics encountered in the control technology based on the orientation of the rotor flux. Broken bar faults can have a significant effect on the induction motor working operation. According to the results, the fault tolerant control algorithm was confirmed effectively. Fault tolerant control in the induction is very important to maintain system performance at an acceptable level. The algorithm used is very effective and has been succeeded to maintain both speed and torque.

Appendix

Motors parameters (Belhamdi 2013)

R_s=7.58(Ω)	Stator resistance
R_r=6.3(Ω)	Rotor resistance
J=0.0054(Kgm^2)	Inertia
N_s=160	Number of turns per stator phase
N_r=16	Number of rotor bars
R_b=0.00015(Ω)	Resistance of a rotor bar
R_e=0.00015 (Ω)	Resistance of end ring segment
L_e=0.1e-6(H)	Leakage inductance of end ring
L_b= 0.1e-6H	Rotor bar inductance
p=2	Poles number
L=65(mm)	Length of the rotor
E=25(mm)	Air-gap mean diameter
L_{1s}=0.0265(H)	Mutual inductance
P=1.1(kW)	Output power
K0=0 (SI)	Friction coefficient
220/380(V)	Stator voltage
50(Hz)	Stator frequency

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