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Performance Comparison of PI and Fuzzy Logic Controllers of DTC for Torque Ripple Reduction

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ABSTRACT

Induction Motors have the wide range of applications due to their advantages like rugged construction, low cost and robust performance. The speed control of induction motor is essential in industrial applications. The Direct Torque Control is the well efficient method for speed control of industrial machines. Direct Torque Control is used to minimize electromagnetic torque and flux ripples. The major problems connected with DTC drives are switching frequency that varies with operating conditions and high torque and flux ripples. In order to improve the performance of the classical DTC, a new modified DTC with the fuzzy logic controller (FLC) is proposed in this paper. The use of FLC is to improve the decoupled control between flux and torque. The paper focused on the Fuzzy Logic Direct Torque Controller (FLDTC) to expand the dynamic performance compared to the classical DTC system. Finally, the results are shown that Fuzzy Logic Direct Torque Controller shows the better performance compared with the PI controllers. Results include simulation in the environment of MATLAB/Simulink.

Keywords: Direct Torque Control, Fuzzy Logic Controller, Induction Motor, PI Controllers.

1. INTRODUCTION

DC machines were widely employed in the applications that require variable speed, because their torque and flux can be controlled via armature and field current. The main drawback of DC motors is the use of commutator which is less effective in case of high speed or high voltage applications and very dangerous in the case of explosive or corrosive materials. For all these reasons, AC machines have recently replaced their antecedent DC machines in most of industrial and domestic applications [1]. Induction machines (IM) are the most commonly used AC machines in industrial applications. IM are reliable, low costly, rugged and available mostly in all sizes. Different methods are used in the control of induction machines among which Direct torque control (DTC) [2], [3] is one of best possible solution for variable frequency drives to control the torque and speed of induction motors. A classical DTC drive system, which is based on a fixed hysteresis bands for both torque and flux controllers, suffers from a varying switching frequency, which is a function of the motor speed, stator/rotor fluxes, and stator voltage; it is also not constant in steady state. Variable switching frequency is undesirable. At low speed, an appreciable level of acoustic noise is present [4]-[7], which is mainly due to the low inverter switching frequency. The high frequency is limited by the switching characteristics of the power devices. Therefore, there will be large torque ripples and distorted waveforms in currents and fluxes. In order to improve the dynamic performance of the classical DTC, a new modified DTC with fuzzy logic controller (FLC) is proposed**.** The present paper deals with the development of a Fuzzy Logic Direct Torque Controller (FLDTC) that is expected to improve the dynamic performance compared to the classical DTC system. The study will cover the possible ways to overcome the disadvantages of the classical DTC method such as, starting problems, distorted current waveforms, variable switching frequency, and existence of high torque pulsation and flux ripple. This new DTFC system is designed and proved by means of simulations.

2. DIRECT TORQUE CONTROL

A block diagram of a DTC system for an induction motor is shown in Figure 1 [8]. The basic configuration of DTC consists of hysteresis controller, torque and flux estimator and switching table. The basic concept of DTC is to control directly the stator flux linkage (or rotor flux linkage or magnetizing flux linkage) and electromagnetic torque of machine simultaneously by the selection of optimum inverter switching modes [8,9]. The use of a switching table for voltage vector selection provides fast response, low inverter switching frequency and low harmonic losses without the complex field orientation by restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made.

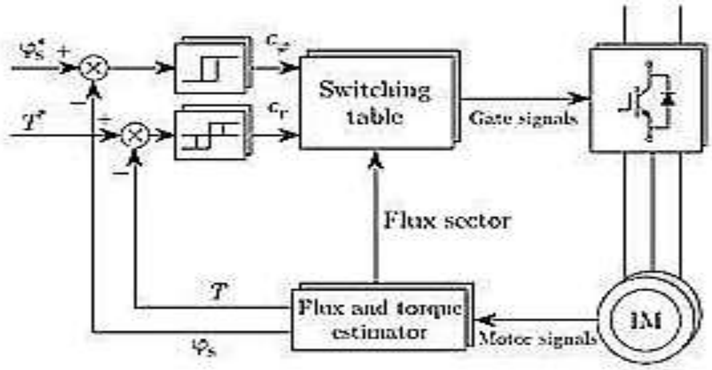

Figure 1: Direct torque control of induction machine

The DTC controller comprises hysteresis controllers for flux and torque to select the switching voltage vector in order to maintain flux and torque between upper and lower limit [10,11] The presence of hysteresis controller which depend on speed, flux, stator voltage and hysteresis band also leads to a variable switching frequency operation, torque ripples and flux dropping at low speed due to the hysteresis comparator used for the torque and flux comparators. These drawbacks affect the result in increased sub-harmonic currents, current. ripple and variable switching losses in the inverter [12]. It is show that, the switching frequency is mainly affected by the torque hysteresis band and increases with the width of the band. For a fixed band controller, it is therefore necessary to set the band to the maximum (or worst case) condition so that the switching frequency is guaranteed not to exceed its limit which is determined by the thermal restriction of the power devices [13]. A fuzzy logic control strategy has been proposed where the band is controlled in real time by variation of the applied voltage vector in order to keep the switching frequency constant at any operation condition. This method reduces the torque ripple while maintaining a constant torque switching frequency

Stator flux is a time integral of stator EMF

$$\frac{d\Psi_s}{dt} = V_S - i_s R_S \qquad (1)$$

Selection of appropriate voltage vector in the inverter is based on stator equation

$$\Delta\Psi_S = \int_0^{TL} (V_s - i_s R_S)dt = V_S(i)T_i \qquad (2)$$

Electromagnetic torque can be expressed as

$$T_E = \frac{3}{2}\left(\frac{P}{2}\right)\Psi_S \qquad (3)$$

$$\Psi_S = \Psi_{qS}\text{-}\, j\Psi_{ds} \qquad (4)$$

$$\mathrm{I}_S = i_{qS}\text{-}\, j\mathrm{i}_{ds} \qquad (5)$$

$$\psi_s = \frac{L_m}{L_r}\psi_r + jL_s \qquad (6)$$

$$\boldsymbol{T_e} = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s}\psi_r X \psi_s \qquad (7)$$

Figure 2 shows the phasor for eq.8 indicating that the vectors, Ψ_s, Ψ_r *and I* for positive developed torque. If the rotor flux remains constant and the stator flux is changed incrementally by the stator voltage *Vs* as shown, the corresponding change of angle γ is and Δγ the incremental torque Δ*T e* is given as

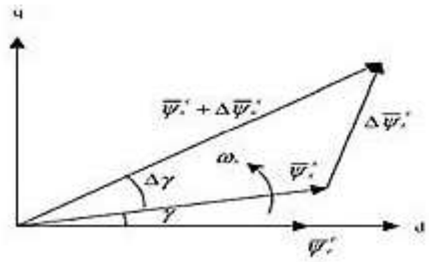

Figure 2: Stator and rotor flux space vector

2.1 DTC Development

The command stator flux and torque magnitudes are compared with the respective estimated values and the errors are processed through hysteresis band controller [14, 15]. The torque control of the inverter fed machine is carried out by hysteresis control of magnitude of stator flux and torque that selects one of the six active and two zero inverter voltage vectors as shown in Figure 3. The selection is made in order to maintain the torque and flux error inside the hysteresis band in which the errors are indicated by Te and ΔΨs respectively.

$$\Delta T_e = T_{eref} - T_e \quad (8)$$
$$\Delta\psi_s^s = \psi_{sref}^s - \psi_s^s \quad (9)$$

The six different directions of *V s* are denoted as *V(i=0,1,2,6).* Considering *Sa, Sb* , and *Sc* as the combination of switches, the status of the inverter are given by eq.11

$$V_i = \frac{2V_s}{3}\left(S_a + e^{\frac{j2\pi}{3}} S_b + e^{\frac{j2\pi}{3}} S_c\right) \quad (11)$$

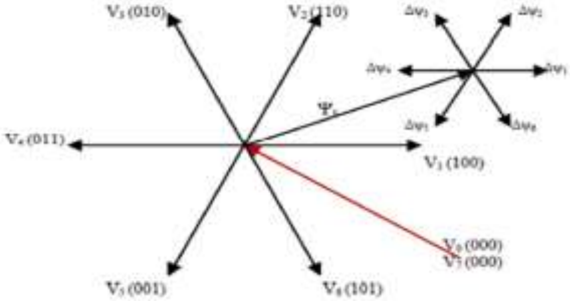

Fig.3 Inverter Voltage Vectors and corresponding stator flux variation in time, Δt

The flux loop controller has two levels of digital output according to the following relations

$$H_\psi = 1\ for\ E_\psi > +HB_\psi \quad (12)$$

$$H_\psi = 1\ for\ E_\psi < -HB_\psi \quad (13)$$

The total hysteresis band width of the flux loop controller is $2H_{\psi}$. The actual stator flux is constrained within this band and it tracks the command flux in zigzag path as shown in Figure 4. The torque control loop has three levels of digital output, which possess the following relation

$$H_{Te} = 1\ for\ E_{Te} > +HB_{Te} \quad (14)$$
$$H_{Te} = 0\ for HB_{Te}\ < E_{Te} > +HB_{Te} \quad (15)$$
$$H_{Te} = -1\ for\ E_{Te} < -HB_{Te} \quad (16)$$

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block computes the sector number in which the flux vector currently lies. There are six active voltage vectors each spanning 60^0. The voltage vector table receives H_Ψ and H_{Te} sector *S* (*i*) and generates the appropriate control for the inverter from a look-up table.

1.2. **Flux and Torque Estimator**

Flux and torque estimators are used to determine the actual value of torque and flux linkages. Into this block enters the VSI voltage vector transformed to the d-q stationary reference frame. The three-phase variables are

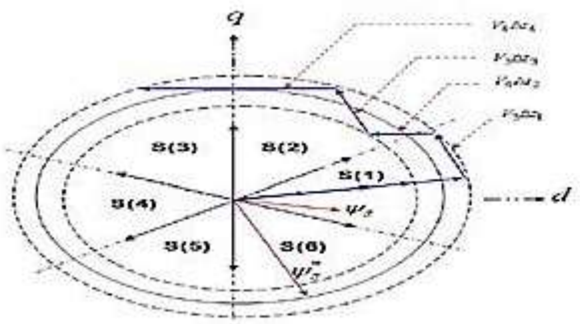

Figure 4: Trajectory of stator flux vector transformed into the d-q axes variables using the following transformation

The d-q axes stator flux linkage is estimated by computing the integral of difference between the respective d-q input voltage and the voltage drop across the stator resistance.

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (17)$$

$$\psi_{ds} = \int (v_d - i_{ds} r_s) dt \quad (18)$$

$$\psi_{qs} = \int (v_q - i_{qs} r_s) dt \quad (19)$$

The resultant stator flux linkage can be expressed as

$$\psi = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \quad (20)$$

The location of the stator flux linkage should be known so that the appropriate voltage vector is selected depending upon the flux location.

$$\theta_e = tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \quad (21)$$

The electromagnetic torque can be expressed as

$$\boldsymbol{T_e} = \frac{3}{2}\left(\frac{P}{2}\right) \psi_{ds} i_{ds} - \psi_{ds} i_{ds} \quad (22)$$

Switching Table

The hysteresis comparator states H_{Te} and H_{Ψ} together with the sector number *S (i)* are used by the switching table block to choose appropriate voltage vector. The switching table implemented is according to Table 1, a high hysteresis state increases the corresponding quantity and vice-versa. The selected voltage vector is synthesized and then sent to the VSI.

Table 1: Switching Table of inverter voltage vector

H_{Ψ}	H_{Ψ}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_0	V_7	V_7	V_0
	-1	V_5	V_6	V_1	V_2	V_3	V_4

3. FUZZY LOGIC CONTROLLER

Fuzzy logic offers a non-analytical choice to avoid the classical analytical control systems.

3.1 Membership Functions

A membership function is a function that describes how much a point or an object in the universe of discourse is related to the universe by giving a degree of membership between 0 and 1. The linguistic variables are not real numbers or integers but they are fuzzy sets. The membership degree or function is the description of how much a given variable belongs to a given set. The functions are designed to make mathematical calculations of linguistic rules and implement them in processing. For each linguistic variable we can assign a membership function η. The choice of membership function in a fuzzy system is the preference of the user. There are no precise rules for the selection of defined membership function or others. However there are some general rules that must be respected to improve the efficiency of a fuzzy logic system. The main rule is that a membership function should overlap just with the nearest membership function.

3.2 Fuzzification of Inputs

The term fuzzification is used to describe the process of expressing the deterministic input variables into linguistic variables. This process is done by choosing suitable membership functions for the different input variables. The input variables are to be normalized to fit into the range of linguistic variables by using suitable gains. The input variable can be either discrete or continuous. In a continuous world of discourse; the number of linguistic variables describing the inputs can vary. It can contain 2, 3, 5, or more membership functions. The fuzzification is done using different operators of fuzzy logic. The operators changes dependent on the application and the preference of the user. The main operators of fuzzy logic are: OR operator, AND operator, NOT operator.

3.3 Structure of Fuzzy Logic Controller

The general structure of fuzzy logic controller has two inputs. The two inputs are usually the error of output of the process to be controlled and the variation of that error. The derivative of the error can help for more stable transients of the process. The error and its derivative are to be scaled with factors Ke and KΔe, these two factors are used to limit the inputs of the fuzzy logic controller to two defined values. The next step is to choose fuzzification membership functions for each one of the inputs. The inference engine type is then designed and all the control rules are chosen and linguistic rules are built.

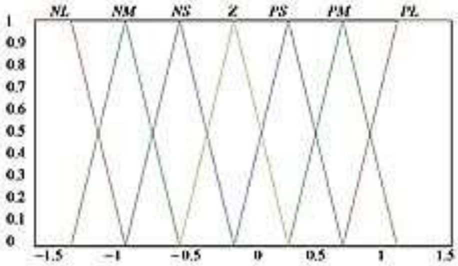

Figure 5: Fuzzification of inputs with seven membership functions

The output of fuzzy controller must then be scaled up to fit the controlled process.

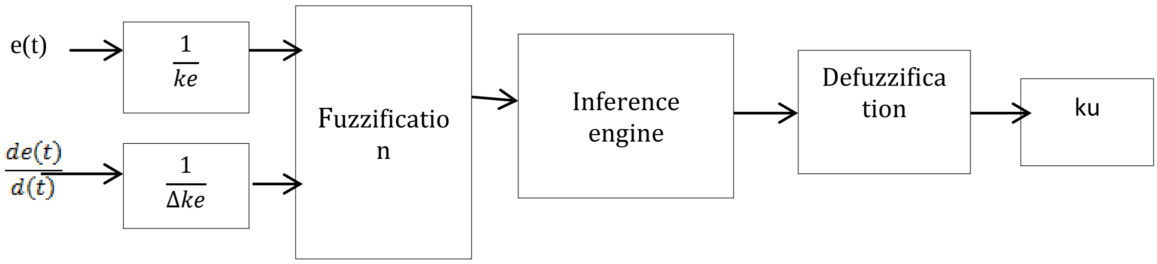

Figure 6: Structure of fuzzy logic controller

This structure is used to build the controller using the membership functions shown Figure. 6 Nine triangular functions were used to cover an error range between -50 and 50. Figure 7. Presents the membership functions of the variations of error. These functions are divided into three parts, one for the negative derivative, one for the null derivative and the last for the positive derivative of error. The output membership functions are shown in Figure 9. Nine membership function were also used in the output to cover the control range of [-1000, 1000].

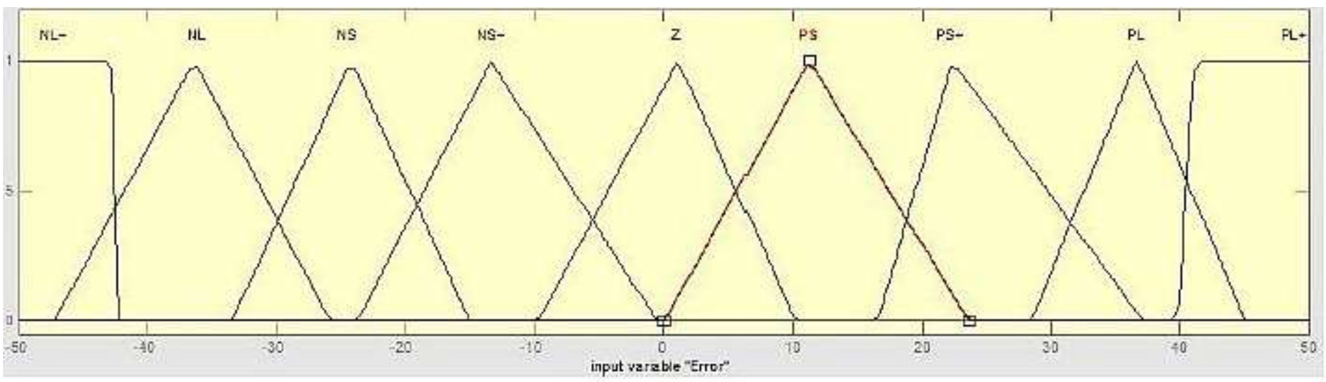

Figure 7: Membership functions of input 1 (Error)

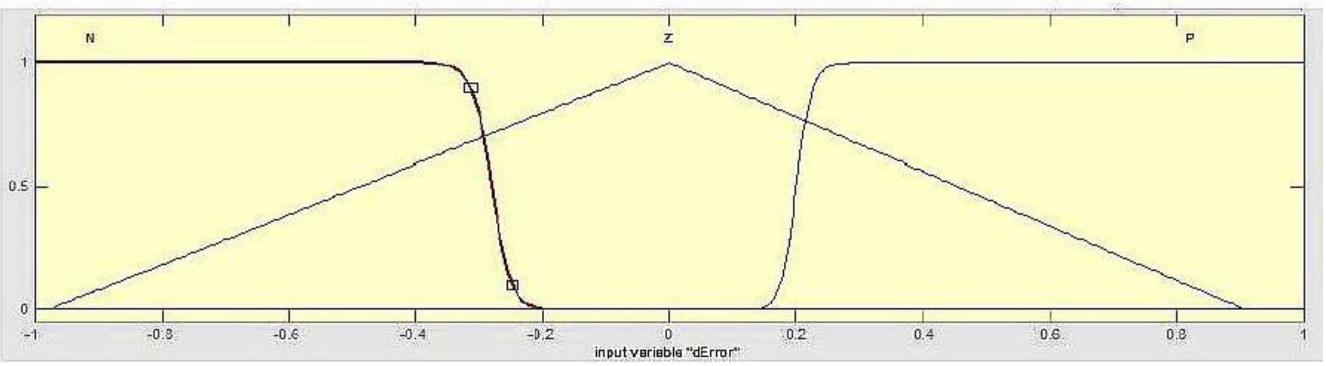

Figure 8: Membership functions of input 2 (derivative of Error)

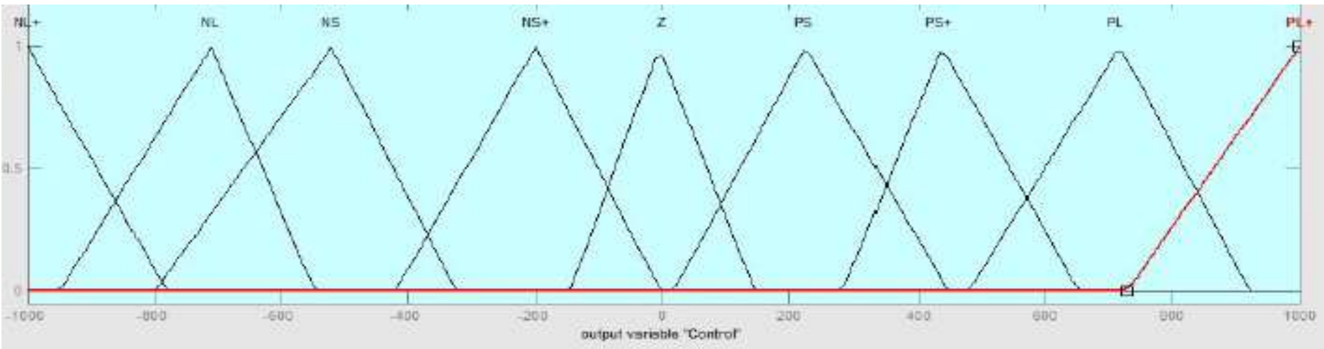

Figure 9: Membership functions of the output (control variable)

Table 2. The controller learning rules of FLC

E \ dE	NL+	NL	NS	NS+	Z	PS	PS+	PL	PL+
N	NL	NS	NS+	Z	Z	Z	PS	PS+	PL
Z	NL	NL	NS	NS+	Z	PS	PS+	PL	PL
P	NL+	NL	NL	NS	NS+	PS+	PL	PL	PL+

4. RESULTS AND DISCUSSIONS

In this paper, the construction of the induction machine, the structure of fuzzy logic controller and the direct torque control method for the speed control of induction machine have been discussed. The direct torque control method as one of the most important and simple control methods of induction machines has been discussed and presented. A fuzzy logic controller will be used instead of the traditional PI controller to increase the stability of system in transient and steady states of the machine. During this work, a Matlab/ Simulink standard three phase induction motor was used. The parameters of the motor are all given in table 3. Three phase power source, three phase bridge rectifier, breaking chopper, and a three phase voltage source inverter were used to supply the induction motor with the need power

Table 3: Parameters of the controlled three-phase machine

Motor Type	Squirrel cage	Stator L	0.3mH	Inertia	3.1 kgm^2
Power	150kw	Rotor R	0.0093Ω	friction	0.08Nms
Voltage	420v	Rotor L	0.3mH	poles	4
Frequency	50Hz	Mutual L	10mH	Stator R	0.148Ω

The general model of simulation circuit consists of rectifier is used to supply with DC voltage that is fed to a chopper. The chopper makes sure that the voltage at the DC side of the rectifier/inverter doesn't exceed certain limit. The inverter is responsible to generate three phase AC control voltages. In this work, two controller types were used namely PI controller and fuzzy logic controller. The reference speed slope is firstly adjusted to avoid any sudden changes in the speed. Sudden speed changes can't be obeyed due to the slow response of motors compared to the other electronic devices. The reference speed is then compared with the measured actual speed of the motor to generate the input of the controller. The error is then fed to the controller to generate the suitable torque value that the motor should generate to make the error zero. For the PI controller, the values of kp=30 and ki=200 were found satisfactory.

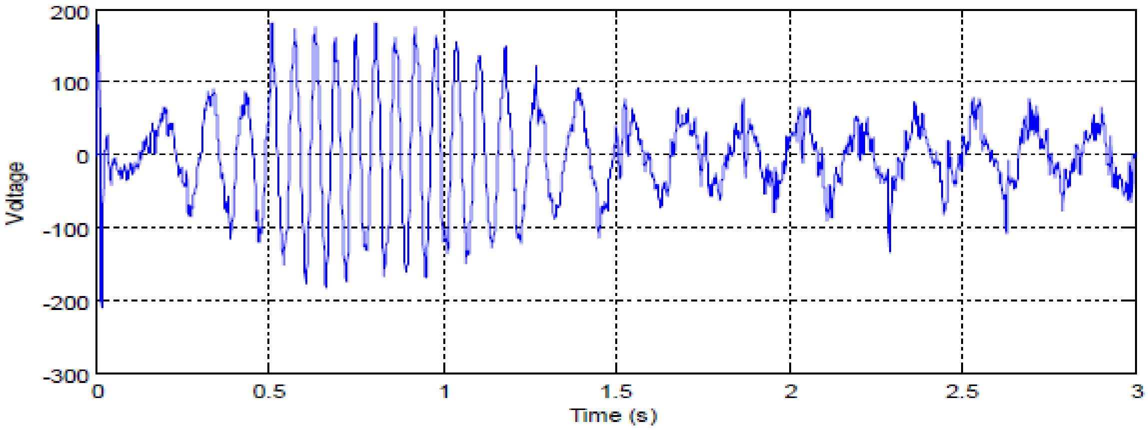

Figure 10: Output voltage of VSI

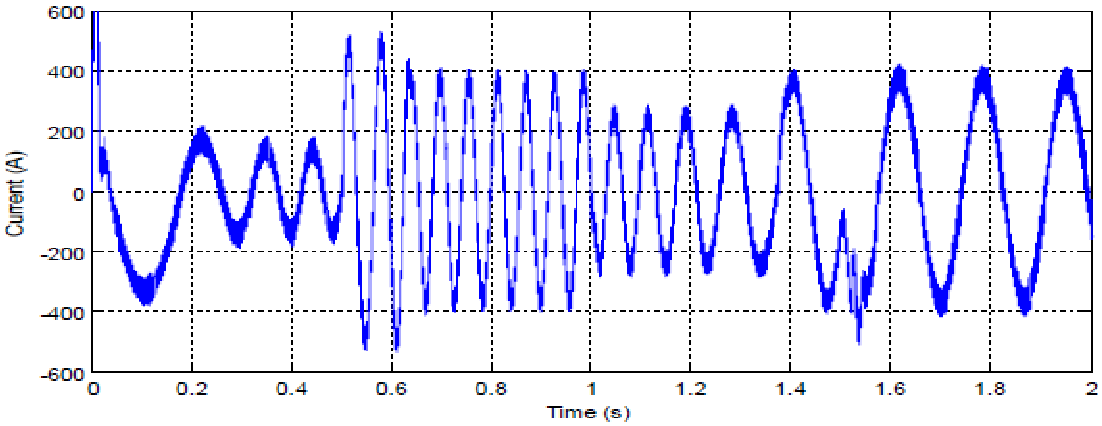

Figure 11: Stator current of phase A

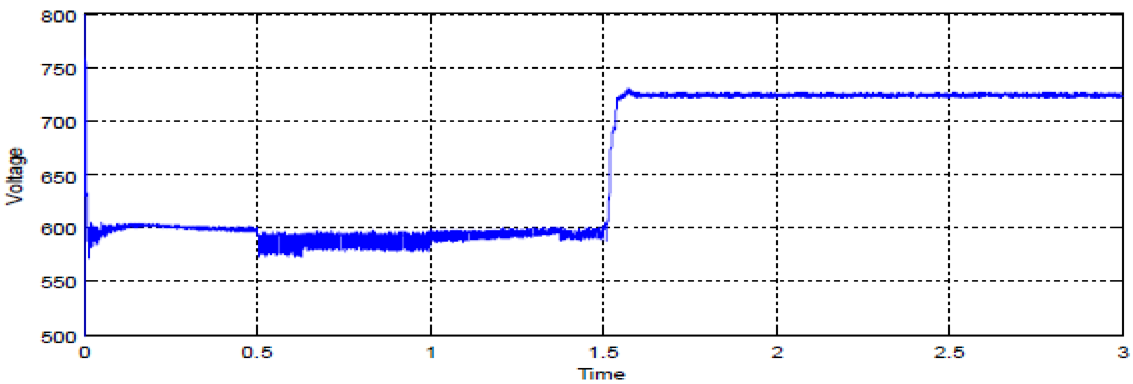

Figure 12: Voltage of DC link capacitor

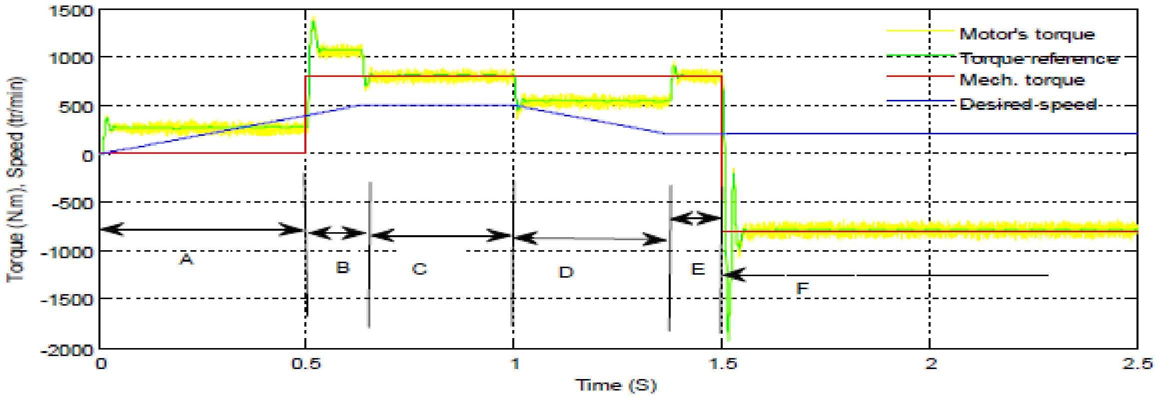

Figure13: Applied mechanical torque on the motor, reference torque generated by the controller, and the torque developed by the motor.

Figure 13, presents the different torques applied on the motor, generated by motor and the reference torque. In zone A, the motor is in start mode and no mechanical torque is applied. The reference torque is not zero as we can see and also the generated torque. This torque is developed to ensure the acceleration of motor from zero to the maximum desired speed and to compensate the mechanical losses due to friction and inertia. In zone B a torque of 800 is applied on the shaft of the motor. The motor develops higher torque to keep the acceleration because it's still in start mode. In zone C, the motor reaches its desired speed and acceleration is now zero. The generated torque is slightly higher than mechanical torque applied on the shaft. In Zone D although the mechanical torque didn't change, the desired speed is reduced. As a result, the motor needs to decelerate and less torque must be developed. The mechanical torque of the load is responsible to decelerate the motor speed in this case. In zone E the motor reaches its constant desired speed. The developed torque is again slightly higher than applied load torque. Finally, in zone F an inverse load torque is applied. The motor works in brake mode to keep speed in its desired values. Figure 13 presents the speed and torque of the motor with no external control. Different values of load torque were applied. The nominal torque of the motor can be found by:

$$\tau_n = \frac{p_n}{w_n} = \frac{1500kW}{1500*\frac{2\pi}{60}} = 955N.m \qquad (23)$$

For that nominal value, the values of 200, 500, and 900 Nm were applied on the motor. It is seen from the Figure that the increase in applied load torque causes a decrease in the speed of an induction motor. The speed of the motor is slightly less than 1500 tr/min and no other possible speeds without external control of the motor.

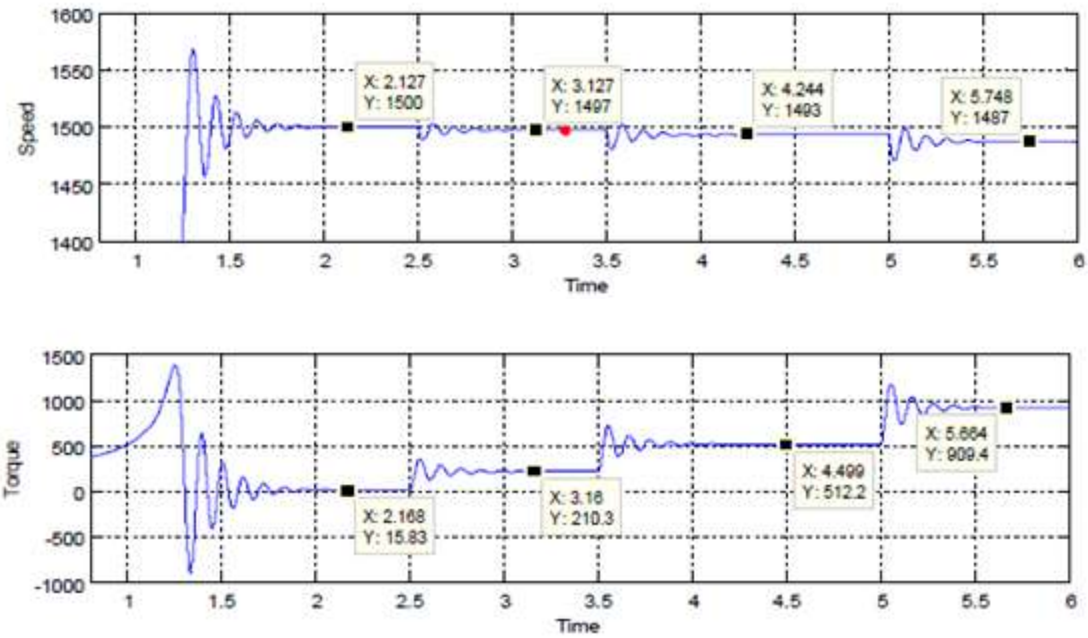

Figure 14: Speed and torque of induction motor with no control under different loads

In order to study the efficiency and robustness of both PI and fuzzy logic controller two different cases were applied. The first case included the application of speed of 500 tr/min initially, this speed is then changed to 200 tr/min at the time of 1 second. At the time of 0.5 second a load torque of 790 Nm was applied on the shaft of the motor and simulation results were recorded. In the time of 1.5 second the load torque was directly inversed and results were recorded. In the second case , the motor was initially set to its full speed under its full load torque. At the moment 1.5s the applied torque was directly inversed. The set speed was changed to 1000 tr/min at the time 2.3s. all results were recorded and will be discussed in the next part of this work.

4.1. Event 1

As mentioned earlier different set speeds and different load torques were applied on the motor in this case. Figure 14 shows the desired speed and obtained speed curve of the motor using PI controller. We can see a slow response time with some static error in the starting moment of the motor and in the moments of speed or torque variations. PI controller is still able to show good results and small errors. Figure 15 presents the torque developed by the motor during the control. Figures 16 and 17 present the stator current and line voltage generated by the VSI. The results obtained by using a FLC controller are presented in Figures 18, 19, and 20. It's clear from Figure 18 that the rotor follows its desired speed perfectly with minimum error and faster response time in case of speed or torque variation. The generated torque and absorbed currents are also presented in Figure 19 and 20.

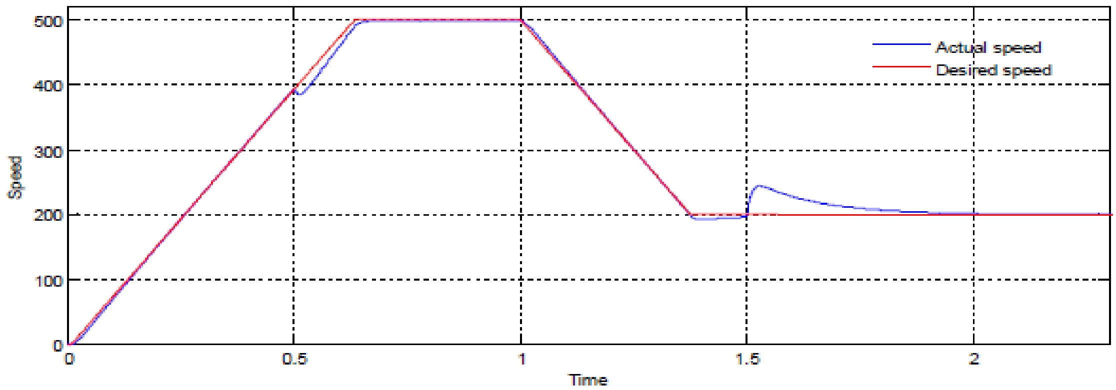

Figure 15: Desired and actual rotor speed in case of PI controller.

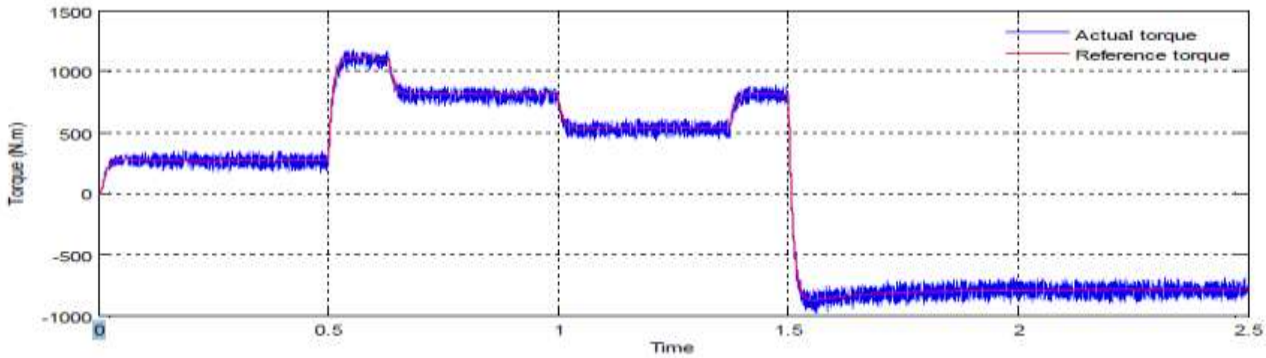

Figure 16: Reference and actual torque of the motor

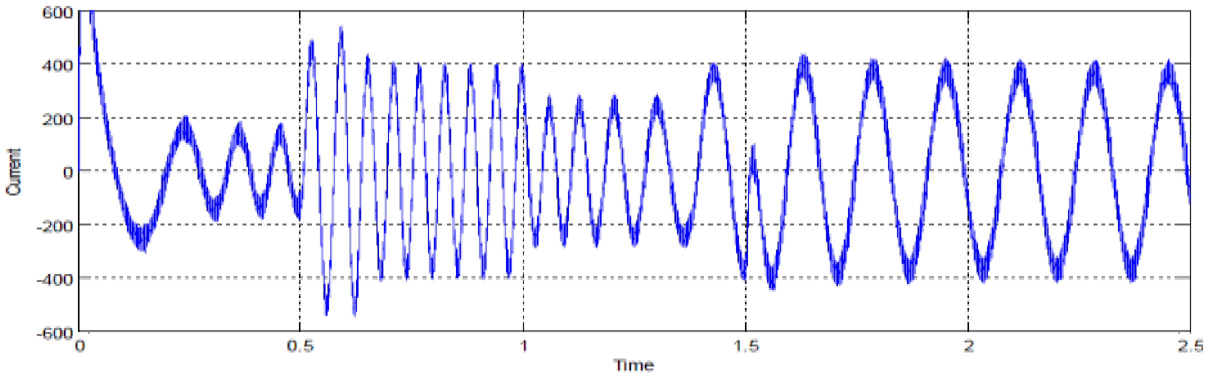

Figure 17: Current of the motor under different speed values

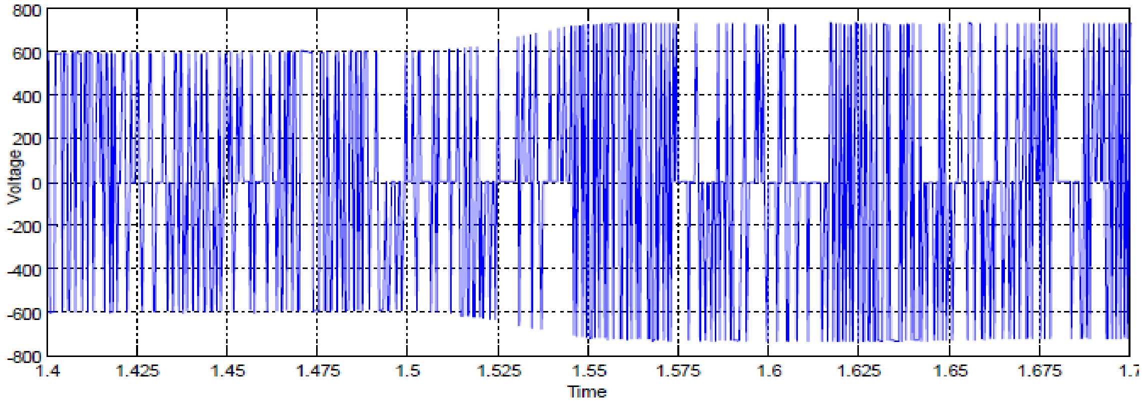

Figure 18: Output voltage of VSI to the motor

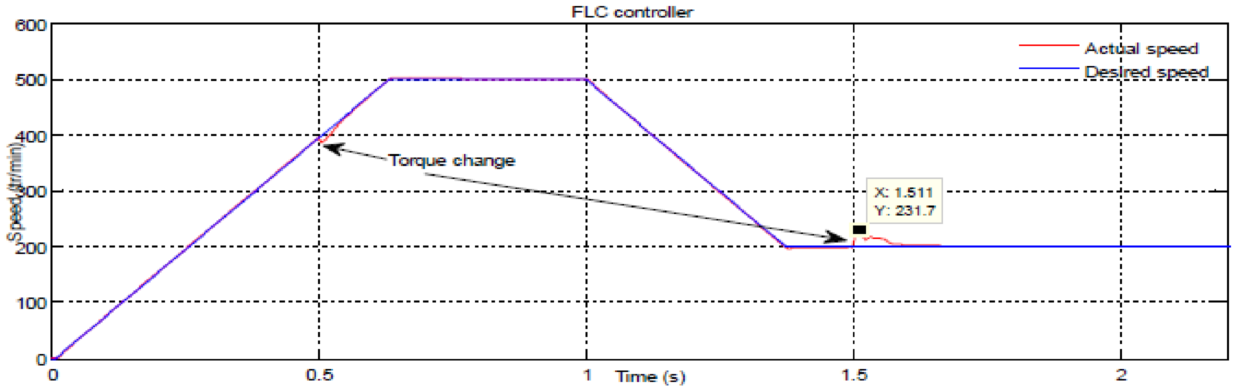

Figure 19: Actual vs. desired speed of motor after using FLC controller

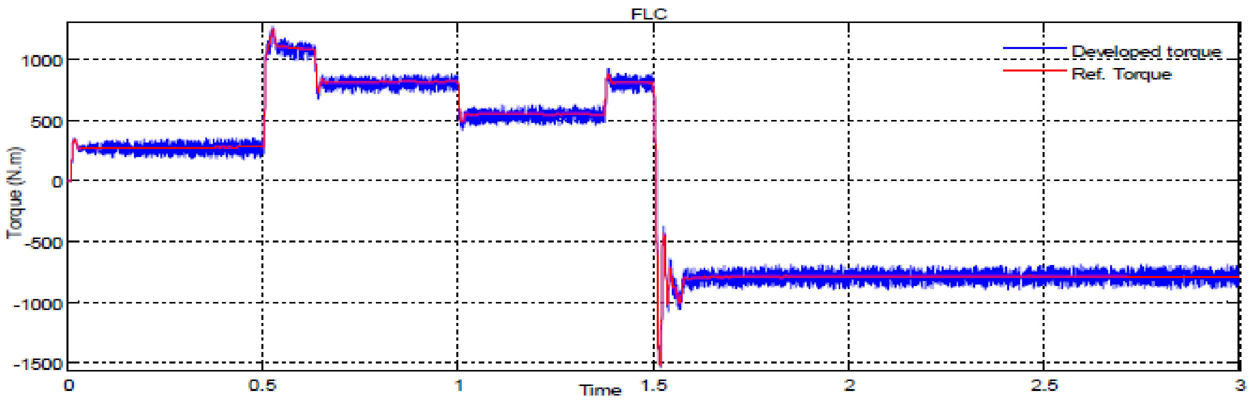

Figure 20: Reference torque and motor torque

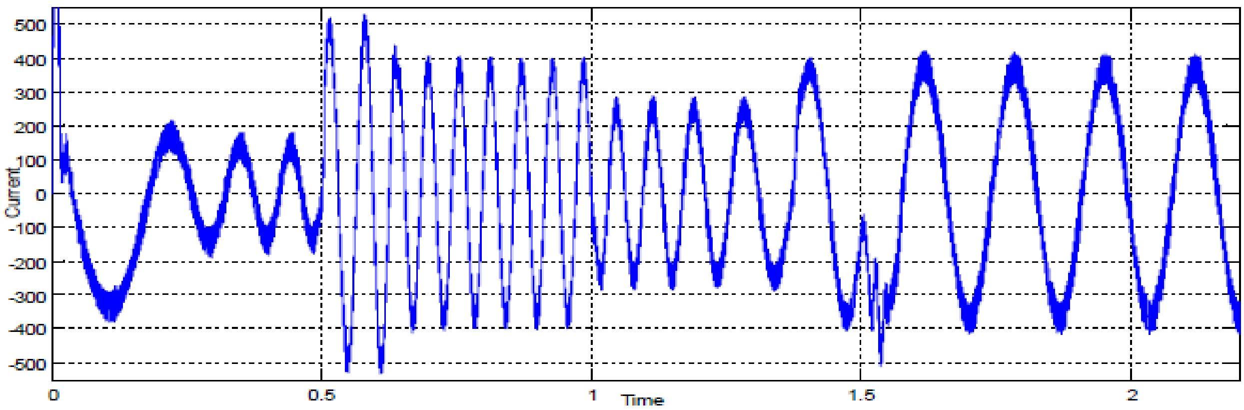

Figure 21: Stator current

4.2 Event 2

In this case, full load torque under full speed was applied on the motor. Load torque is presented in Figure 21. The Figure.23 presents the desired and actual speed of the motor controlled using fuzzy logic with DTC controller. Speed is following its desired value fast with minimum error. The developed torque is presented in Figure 24. The results obtained using PI controllers are presented in Figures 25 and 26. Figure 25 shows the speed of the motor compared to its desired value. We can see that the PI controller has limited capability to keep track of the desired speed in case of fast changes in reference speed. A speed error of more than 200 was detected at full speed. Over more, very slow response was achieved using this controller.

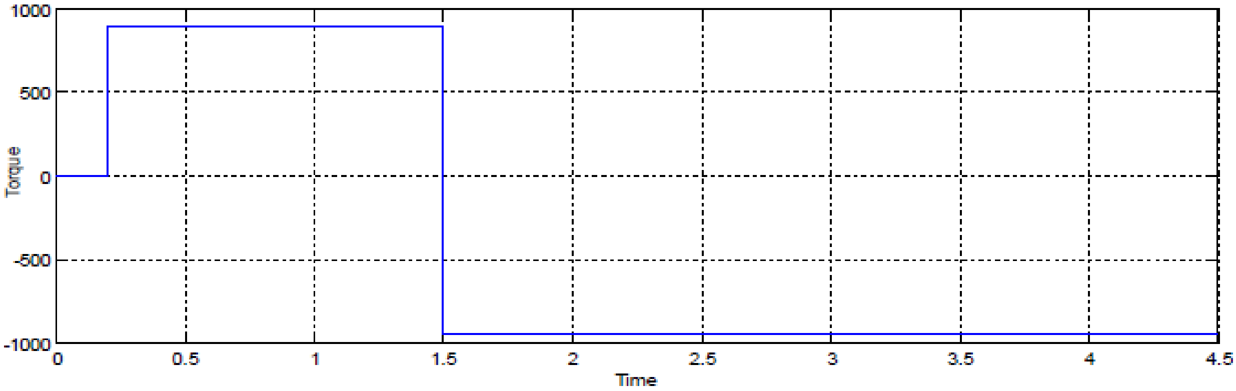

Figure 22: Applied load torque in event 2

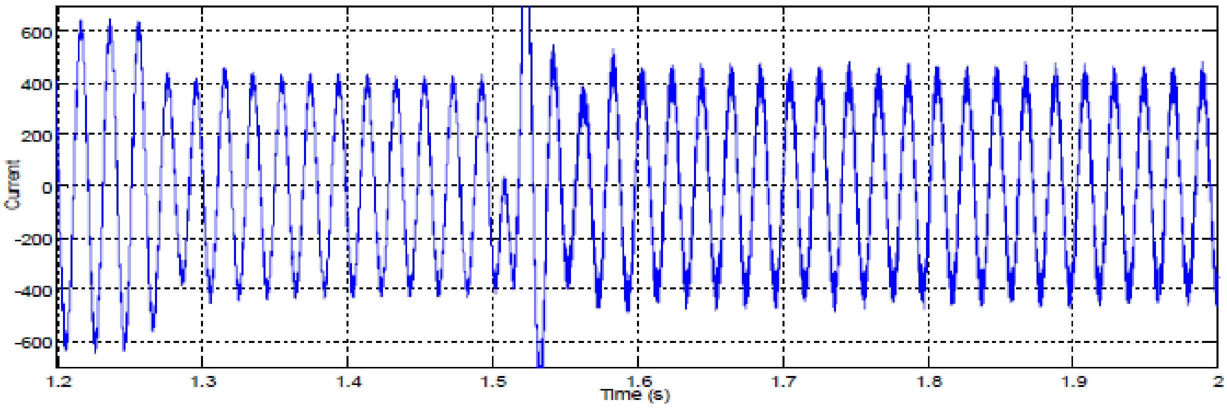

Figure 23: Stator current in the case of fuzzy controller

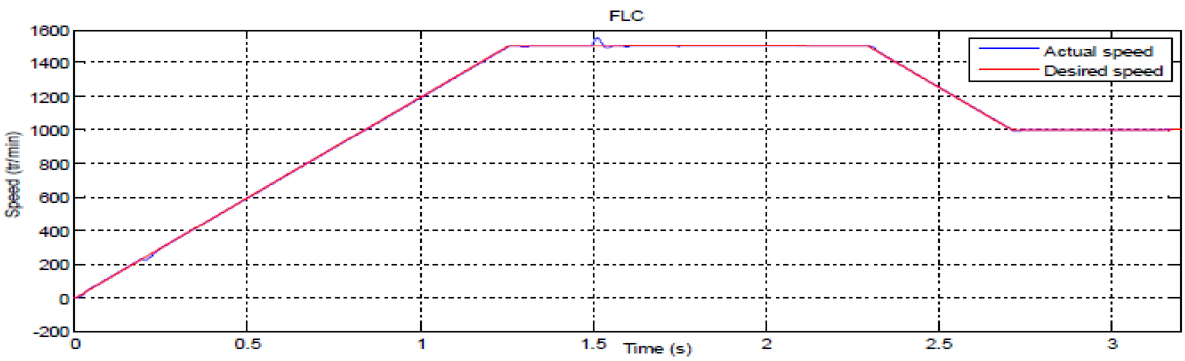

Figure 24: Rotor Speed under FLC control

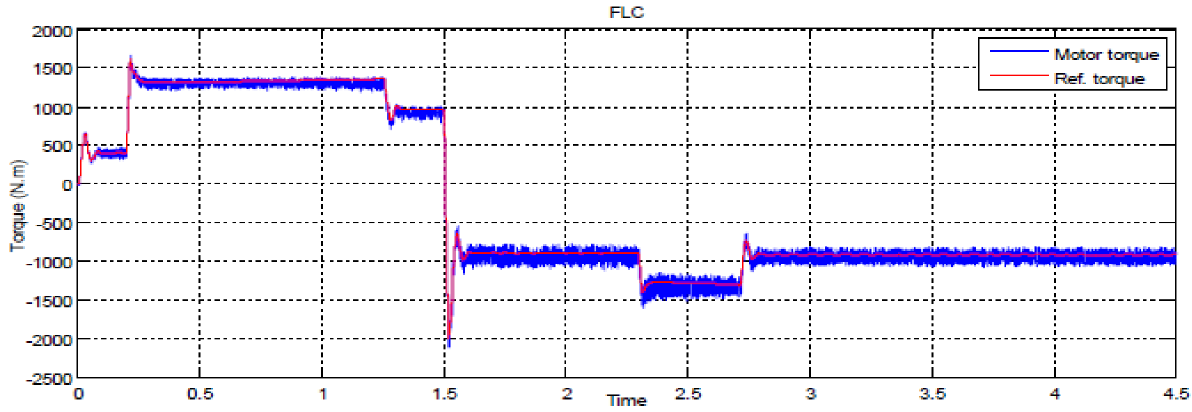

Figure 25: Motor torque

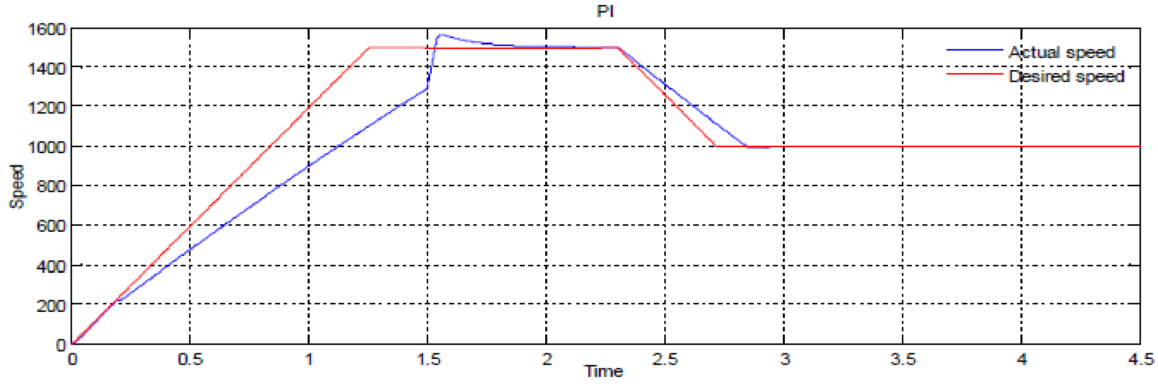

Figure 26: Rotor speed using PI controller

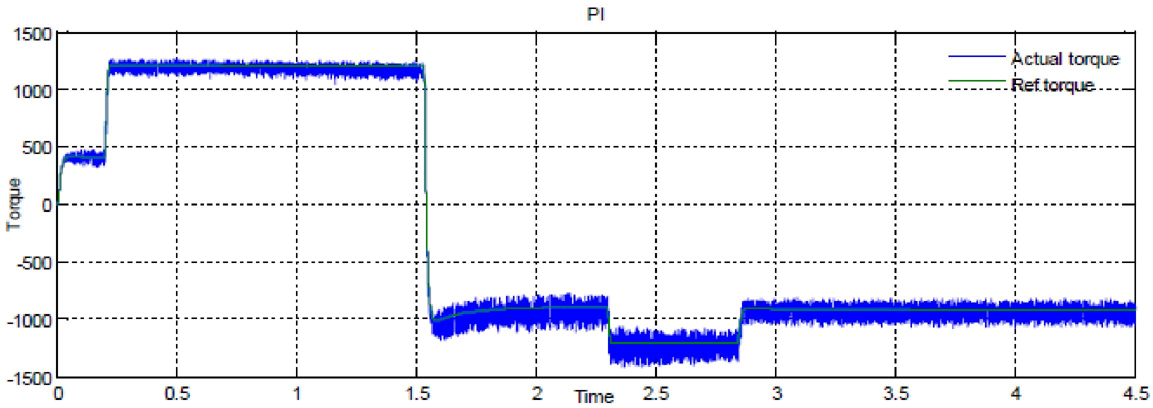

Figure 27: Torque of the motor

The table below presents a comparison between the results obtained by using a PI and FLC controller in the two studied cases. The comparison includes the static, dynamic error, and the transient time before the motor speed reaches its dynamic phase. We can notice that the fuzzy logic controller is faster in response with less transient fluctuations.

Table 4: Comparison between PI and FLC performance

	Event1		Event2	
	PI	FLC	PI	FLC
Static Error	0	0	0	0
Dynamic Error	25%	15%	3%	1%
Transient(s)	0.4	0.2	0.5	0.1

5. CONCLUSIONS

The results and discussions includes the induction motors using DTC method with fuzzy logic controller. In most of studies, the DTC was combined with PI controller for speed regulation. The use of fuzzy controller was proposed in this paper to increase the accuracy of speed results in addition to the ability of fuzzy logic controller to react against sudden changes and non linearity of the system. DTC control has also proved its ability to keep track of desired speed values with minimum costs and efforts in addition to simple implementation. The method is an easy method with light amount of calculations and no need for any reference transformation or synchronization. The method implies no closed loop control of the voltage source inverter. Only two current sensors and three voltage sensors in addition to a speed sensors are need to implement the method. From the obtained results we can conclude that fuzzy logic controller with DTC method is a very excellent choice for the control of induction machines in term of low cost, simplicity, and efficiency. The control has shown the ability of this method to track different speed values with perfect response away from very low speeds. In this paper an improvement in the control of induction motor control using DTC control method was achieved. Improved results with sudden changes in the desired speed were achieved by replacing the traditional PI controller by a non linear fuzzy logic controller. That is, higher stability of the control system and the machine is achieved in addition to fast and exact system response. That makes this method more suitable for systems that require high accuracy of speed and impose continuously variable speed drive. As future plans, this work opens the doors widely for better understanding of different control schemes and comparative studies between these schemes.

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