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Implementation of Indirect Vector Control of Induction Motor Speed using Fuzzy Controller

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Abstract:
Induction motors are commonly used in today's industry because of its variable speed applications. Even though it was considered that the control of speed of induction motor is not feasible beyond a range, with advent of technology variable speed drives were developed. Earlier stage controllers were P and their derived controllers. The term fuzzy means vagueness. So the fuzzy controller implemented for speed control takes into the vague values in the system and provides a steady control for the smooth working of the system. The use of these controllers helps in solving the unknown parameters problems and provides an efficient speed control of induction motors compared to its non-intelligent counter parts. The unknown parameter variations in motor, causing losses, chattering of torque etc. can be accounted for in the AI controllers.

Keywords: *Dynamic Simulation, Fuzzy Controller, Indirect Vector Control, Hysterisis Band Current Controller, Voltage Source Inverter*

1. Introduction

Industries around the world today, use drives for various applications. The applications include electric vehicles, pumps, elevators, fans, home appliances, paper and textile mills, wind generation etc. The electrical machine is the main part of the drives. Even when the machines were introduced hundreds of years ago, the research and development in their field appear to be continuing even today. So efficient working of these electrical machines leads to the robust working of the drive and thus the maximum efficiency of the application. Out of the electricity produced today majority is consumed by industrial applications which mainly uses electrical machines. Out of electrical machines about 85-90% is induction machines. For a long period of time induction motors were used as constant speed application drive. With the discovery of power electronics devices, the variable speed drive for induction motor could be implemented. In the same period of time, there were advances in control methods as well as Artificial Intelligence (AI) techniques. Artificial Intelligent techniques include making use of fuzzy logic, neural networks, genetic algorithm etc. Later on researchers concluded that induction motor drive performance enhances when artificial intelligence based methods are adopted. Fuzzy logic control, neural network control, genetic algorithm, and expert system exhibits superiority among the existing intelligent control technologies. Since Artificial Intelligent Controllers (AIC) possesses advantages in comparison with to conventional PI, PID and their adaptive versions, they are considered best controllers for Induction motor drive.

Even though the parameters and load varies during motor operation, it is desirable to provide a controlled performance in transient as well as steady state operation. Unless the conventional controllers have high gain these requirement5s cannot be provided since they have fixed parameters. Hence, control strategy should be robust and adaptive .AIC controllers can account for robustness as well as additivity. This paper explains how fuzzy controller is implemented for induction motor drive.

2. Dynamic Modeling of Induction Motor

An induction or asynchronous motor is an AC electric motor. Electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. They are of two types of induction motors,

i. Squirrel cage
ii. Wound rotor

Three-phase squirrel-cage induction motors are used in industrial drives because of their ruggedness, reliability and since they are economical. They are also increasingly being used in variable-frequency drives (VFDs) with variable-speed application

2.1. Modeling of Induction Motor Drive

Induction motor dynamic behavior can be expressed by time varying voltage and torque. The differential equations that govern to dynamic model of induction motor are sophisticated [i]. These equation complexities can be decreased by converting the analysis plane from poly phase plane (a-b-c) to two phase plane (q-d). Clarks and Parks transformations are used to convert the induction motor from a-b-c to d-q frame. That is stator and rotor variables such as voltage, current and flux linkages of an induction machine are transferred to another reference plane which is considered stationary.

For simulation of induction motor state space modeling with stationary stator frame is implemented [ii]. Stator inductance of a machine is the sum of the stator leakage inductance and magnetizing inductance ($L_{ls} = L_s + L_m$), similarly for rotor, rotor inductance is the sum of the rotor leakage inductance and magnetizing inductance ($L_{lr} = L_r + L_m$). From the equivalent circuit of the induction motor, the model equations can be derived as,

$$\frac{1}{\omega_b}\frac{dF_{qs}}{dt} = V_{qs} - \frac{\omega_e}{\omega_b}F_{qs} - R_s i_{qs} \qquad (1)$$

$$\frac{1}{\omega_b}\frac{dF_{ds}}{dt} = V_{ds} - \frac{\omega_e}{\omega_b}F_{ds} - R_s i_{ds} \qquad (2)$$

$$\frac{1}{\omega_b}\frac{dF_{qr}}{dt} = V_{qr} - \frac{\omega_e - \omega_r}{\omega_b}F_{qr} - R_r i_{qr} \qquad (3)$$

$$\frac{1}{\omega_b}\frac{dF_{dr}}{dt} = V_{dr} - \frac{\omega_e - \omega_r}{\omega_b}F_{dr} - R_r i_{dr} \qquad (4)$$

By substituting the values of state variables in (1), (2), (3), (4) the following current equations are obtained

$$i_{qs} = \frac{F_{qs} - F_{mq}}{X_{ls}} \qquad (5)$$

$$i_{ds} = \frac{F_{ds} - F_{md}}{X_{ls}} \qquad (6)$$

$$i_{qr} = \frac{F_{qr} - F_{mq}}{X_{lr}} \qquad (7)$$

$$i_{dr} = \frac{F_{dr} - F_{md}}{X_{lr}} \qquad (8)$$

Where F_{mq} and F_{md} are written as follows:

$$F_{mq} = X_{ml}\left(\frac{F_{qs}}{X_{ls}} + \frac{F_{qr}}{X_{lr}}\right) \qquad (9)$$

$$F_{md} = X_{ml}\left(\frac{F_{ds}}{X_{ls}} + \frac{F_{dr}}{X_{lr}}\right) \qquad (10)$$

$$X_{ml} = \frac{1}{\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}} \qquad (11)$$

The speed ω_r and the torque are related to each other by mechanical equation:

$$T_e = T_{load} + J\frac{2}{P}\frac{d\omega_r}{dt} + B\omega_r \qquad (12)$$

So ω_r is obtainable from above equation (12), where P is the number of poles and J is the moment of inertia.

2.2. Simulation

The dynamic model of an induction motor is explained, in the previous section. The model constructed using that equations was the simulated in MATLAB/SIMULINK as shown in figure 1.The rotating a-b-c reference frame is converted into α-β reference frame by Clark's transformation. Since both a-b-c and α-β reference frame are rotating at synchronous speed, they are stationary with respect to each other. The voltages are transformed from rotating α-β to stationary two phase d-q axes using Parks transformation and are then applied to induction motor. The modeling of induction motor is done using the equations (1)-(12). The motor is considered to have s stationary reference frame for the ease of modeling. The input given is d and q axis voltages and output obtained is torque and current Inverse park transformation is applied in the last stage the stator and rotor currents of induction motor in three phase phases. The implementation is done on bases of inverse park equation

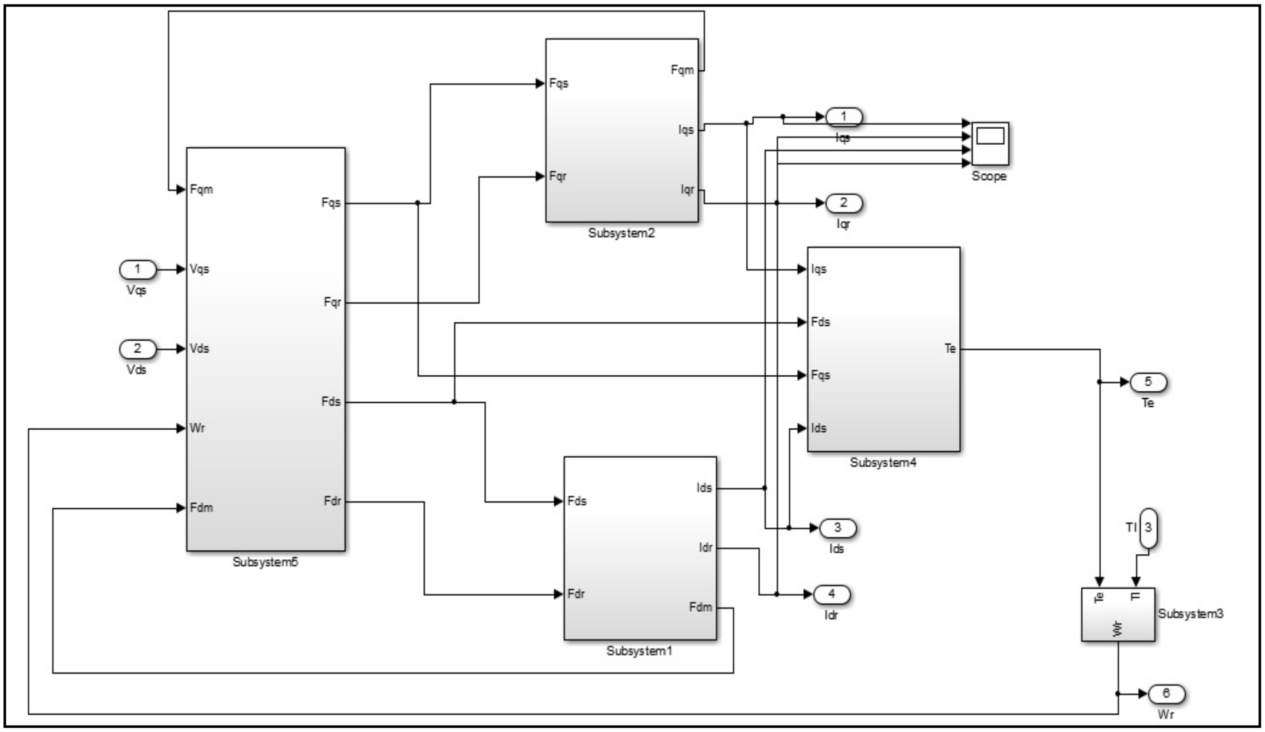

Figure 1: Dynamic modeling of induction motor.

Voltages transformed from three phase a-b-c axis to two phase d-q axes, are then applied to induction motor. Theses voltages drive the motor, giving output as torque, speed and current. Inverse park transformation is applied in the last stage to obtain the stator and rotor currents of induction motor in three phases.

3. Indirect Vector Control of Induction Motor

In the indirect vector control the unit vector signals are generated in feed-forward manner. It is very popular in industrial application. With the help of phasor diagram figure 2 explains the principle of indirect vector control [iii]. The d^s-q^s axis is stator axis which is stationary, but of d^r-q^r axes are rotor axis moving at speed ω_r. Synchronously rotating axes d^e-q^e is rotating ahead of the d^r-q^r axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl}. $\omega_e = \omega_r + \omega_{sl}$,

Therefore we can write

$$\theta_e = \theta_r + \theta_{sl} \qquad (13)$$

The rotor pole position is changing with rotor position at frequency ω_{sl}. For indirect vector control, the stator flux component of current i_{ds} is assumed to be aligned on the d^e axis, and the torque component of current i_{qs} along q^e axis. For control, the control equations used in indirect vector control are

The reference torque component of the stator current

$$I_{qs}^* = \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m}\frac{T_e}{\varphi_{est}} \qquad (14)$$

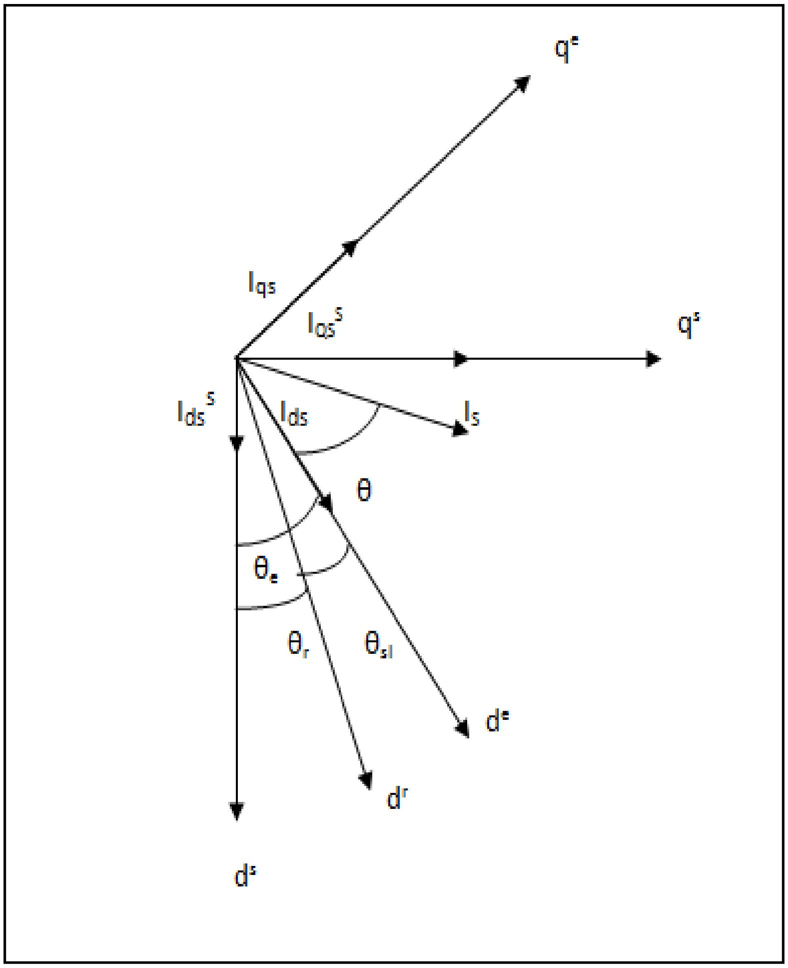

Figure 2: Indirect vector control

Where

$\varphi_{est} = \frac{L_m I_{ds}}{1+T_r S}$ (15)

Therefore the slip speed

$\omega_{sl} = \frac{L_m I_{qs}}{T_r \varphi_{est}}$ (16)

The reference field component of the stator current

$I_{ds}^{*} = \varphi_r^{*}/L_m$ (17)

Implementing the above equations helps us in realizing the implementation of flied oriented control of induction motor.

4. Fuzzy logic Controller

The speed of induction motor is controlled by using the fuzzy controller. The equation used to represent the triangular membership functions in fuzzy logic is:

$$f(x,a,b,c) = \left\{ \begin{matrix} 0, x < a \\ \frac{x-a}{b-a}, a < x < b \\ \frac{c-x}{c-b}, b < x < c \end{matrix} \right\}$$

In the fuzzy controller proposed there are two inputs that are error and change in error [iv]. These two inputs are compared on the bases of rules implemented to give output based on the center of area method. In figure 3, figure 4 the membership functions of Δe, e and control are given, three scalar values of each triangle that are applied into this controller are shown.

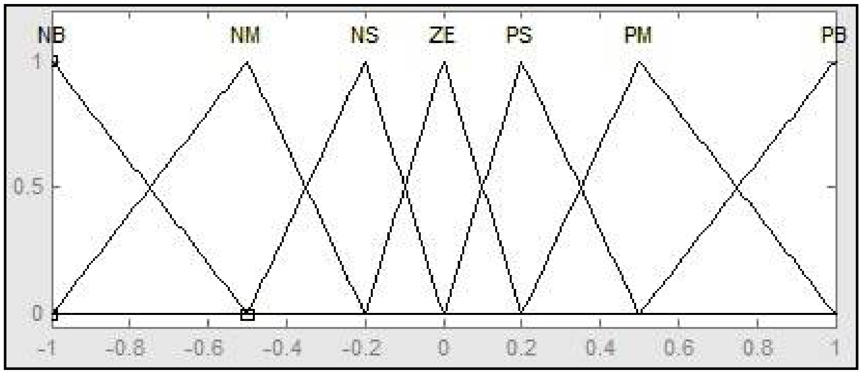

Figure 3: Membership functions for error signal.

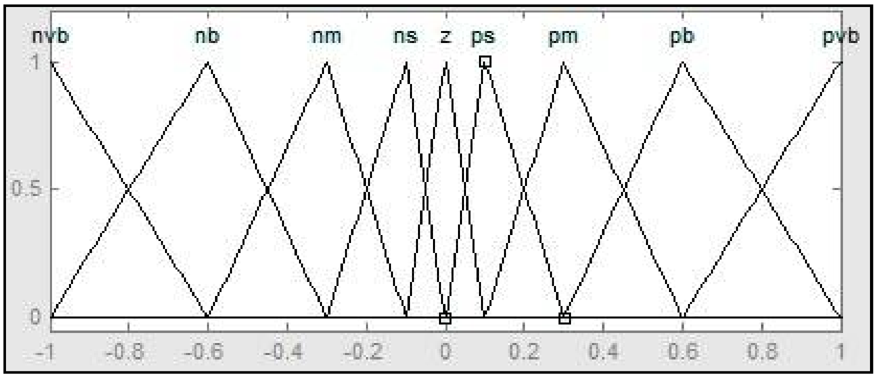

Figure 4:.Membership function for control signal

In table 1 the fuzzy rules decision implemented into the controller are given. The inputs and outputs are related with each other as in the table1. The speed output terminal of the induction motor is compared with the reference speed to create error signal. The error signal and change in error signals are then fed to the fuzzy controller. These signals which are crisp values are then normalized for calculation purpose. Then depending on the data base, rule base and the rules provided an output is calculated using center of area method. This output is then de-normalized to get the original crisp value, which is then used for further calculation.

$e/\Delta e$	NB	NM	NS	ZE	PS	PM	PB
NB	nvb	nvb	nvb	nb	nm	ns	z
NM	nvb	nvb	nb	nm	ns	z	ps
NS	nvb	nb	nm	ns	z	ps	pm
Z	nb	nm	ns	z	ps	pm	pb
PS	nm	ns	z	ps	pm	pb	pvb
PM	ns	z	ps	pm	pb	pvb	pvb
PB	z	ps	pm	pb	pvb	pvb	pvb

Table 1: Rule Base for Fuzzy Logic Controller.

Figure 5 gives the surface three dimensional views of the rules connecting two input variable and output variable.

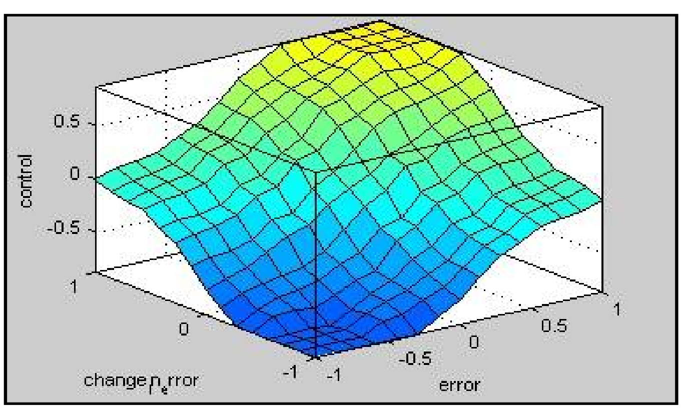

Figure 5: Rule base of fuzzy logic controller

5. Current Controller and Voltage Source Inverter

5.1. Current Controller

Reference [v] explains principle of operation of pulse width modulation implemented. The reference sine wave is generated from fuzzy logic control circuit with desired magnitude and frequency, and is then compared with the actual current wave taken as a feedback from the motor. If the resultant current is more than prescribed upper hysteresis band, the switch in the upper half-bridge turns off and the switch in lower half bridge is turned on. So the current starts decaying since the voltage starts transition from +0.5Vd to -0.5Vd. When the current becomes lesser than the lower hysteresis band, the switch in lower half bridge is turned off and the switch in upper half bridge is turned on. This causes the tracking of the reference sine wave by actual current wave between the upper and lower hysteresis band by switching of the upper and lower half bridge switches. Thus the current controller produces pulses for switching on and off of the switches of voltage source inverter. The inputs to current controller are three phase reference as well as actual currents, and outputs are switching pulses for turning on and off of switches of the PWM inverter. Hysteresis block is provided for each phase so as to feed the three phase current errors. The output of current controller, that is the pulses, is fed to voltage source inverter driving the induction motor.

5.2. Voltage source inverter

The output value from Fuzzy Controller is utilized in changing the frequency of gating signals fed to the PWM inverter. So the AC signals obtained from the inverter will be changing frequency sine waves. The sine wave, which is generated as per output from the current controller, is with specific amplitude and frequency. Three control signals are thus compared with the output currents of the motor to produce controlling pulses for the voltage source inverter. The inverter is basically a voltage source inverter with six switches with three switches in the upper bridge and three switches in the lower bridge [vi]. At the starting point of motor the speed being zero error will be at maximum. Hence the output of fuzzy controller will be minimum resulting in lower frequency of ac supply voltage to the motor from the voltage source inverter. As the motor starts to speed up and the error decrease, the output of the fuzzy controller increases, thus increasing the frequency of the ac input to the motor.

The diagram of PWM inverter is shown in figure 6.

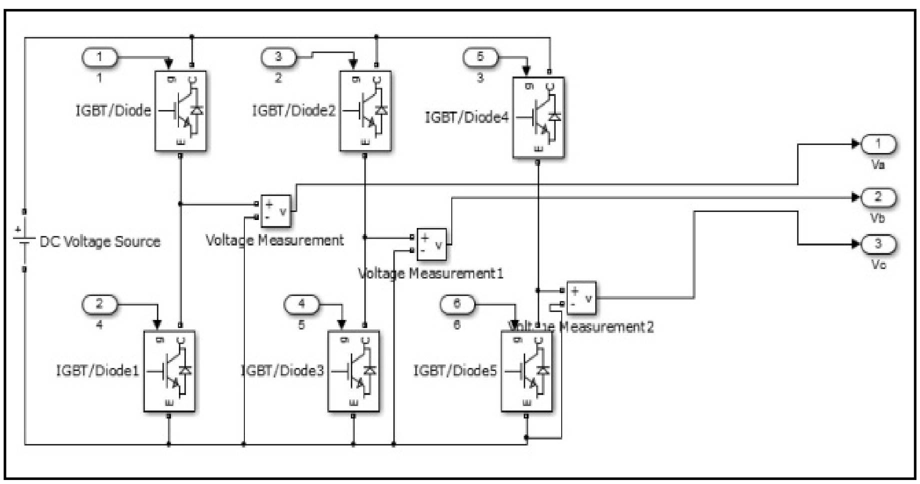

Figure 6: Voltage source inverter

The input to each switch is the gating signals which are produced in current controller block. The firing signals are applied to IGBT gates that will turn ON and OFF the IGBTs according to the following logic. When Vcontrol1 ≤ Vcontrol1* then IGBT1 is ON, IGBT4 is OFF. When Vcontrol1 ≥ Vcontrol1$^$* then IGBT1 is OFF, IGBT4 is ON. When Vcontrol2 ≤ Vcontrol2* then IGBT3 is ON, IGBT6 is OFF. When Vcontrol2 ≥Vcontrol2* then IGBT3 is OFF, IGBT6 is ON. When Vcontrol3 ≤ Vcontrol3* then IGBT5 is ON, IGBT2 is OFF. When Vcontrol3 ≥Vcontrol3* then IGBT5 is OFF, IGBT2 is ON.

6. Simulation and Results

The simulation work is done in MATLAB.A simulation model for voltage source inverter fed induction motor drive with the proposed FLC has been developed. The performance of the fuzzy controller based induction motor drive was studied. The results of simulation for induction motor along with its characteristics are given below

Figure 7 shows the simulation diagram of the proposed system. The error between the reference speed and actual speed of the induction motor is fed to the fuzzy controller along with the change in error. These signals are normalized inside the fuzzy controller, rules are applied and output obtained is de-normalized. The output of the fuzzy controller along with other estimated signals are used to synthesize command signals I_{qs}* and I_{ds}*. These signals along with θ_e is fed into the vector rotators to obtain command signals i_a*, i_b* and i_c*. Three signals are then compared with the actual output current i_a, i_b, i_c in the current controller to generate pulses for the voltage source inverter.

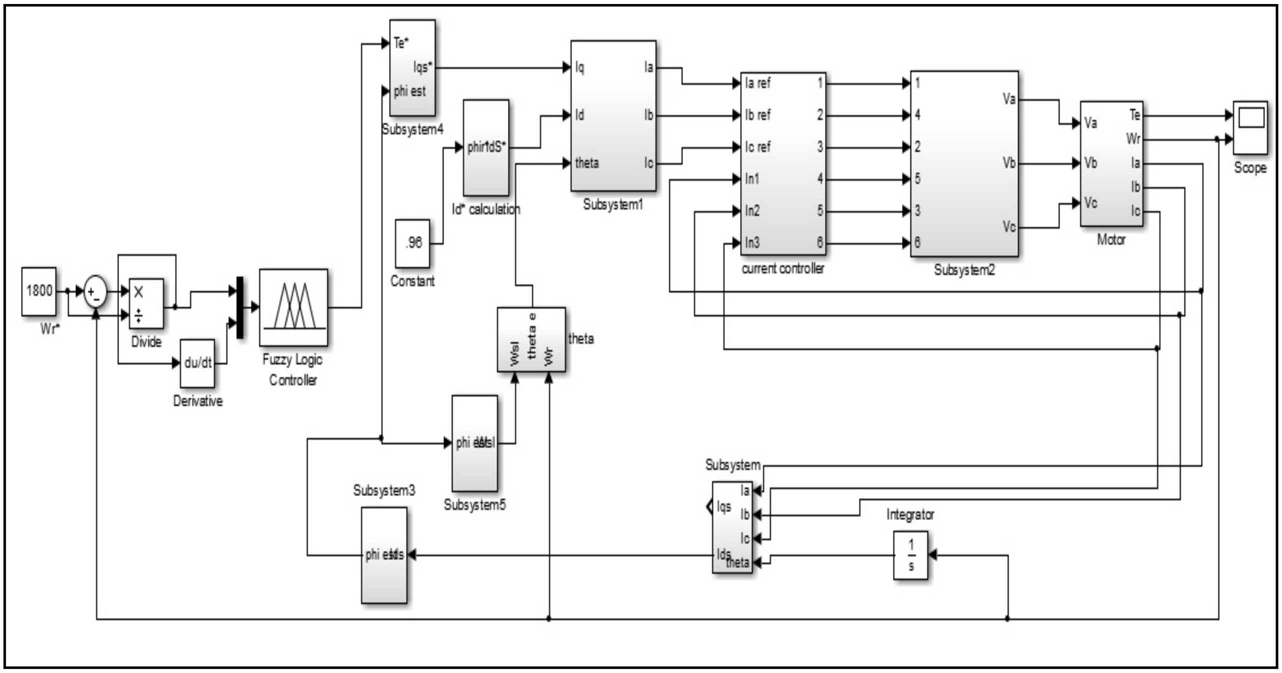

Figure 7: Simulation model of the motor drive

The output of the voltage source inverter is then fed to the induction motor for speed control of the induction motor.

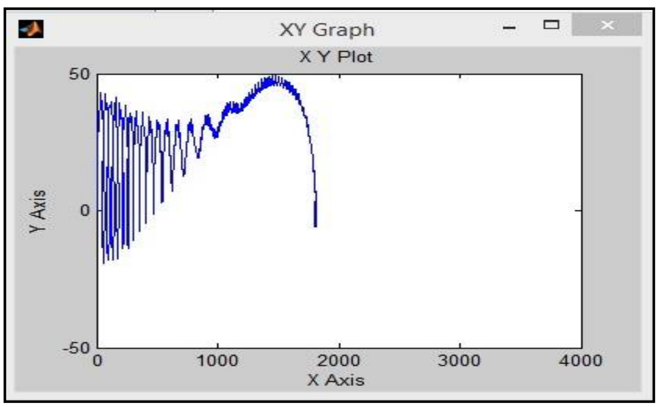

Figure 8: Torque-speed characteristics of IM

Figure 8 shows the torque speed characteristics of induction motor drive. Here torque is represented along y axis and speed is represented along x axis .From figure it is clear that when the speed reaches its rated value the torque settles to zero.

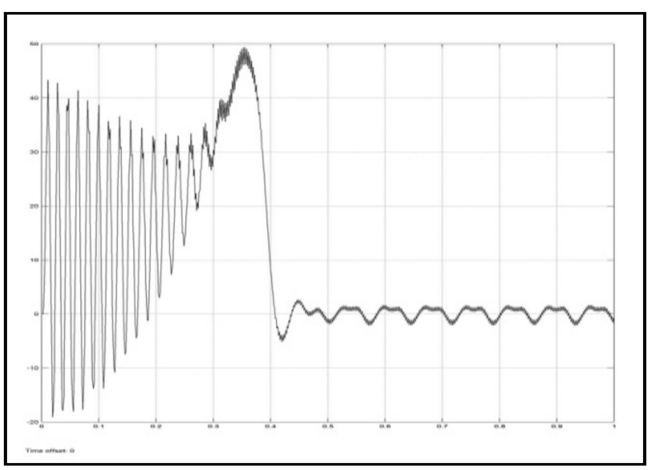
Figure 9: Torque characteristics of IM drive

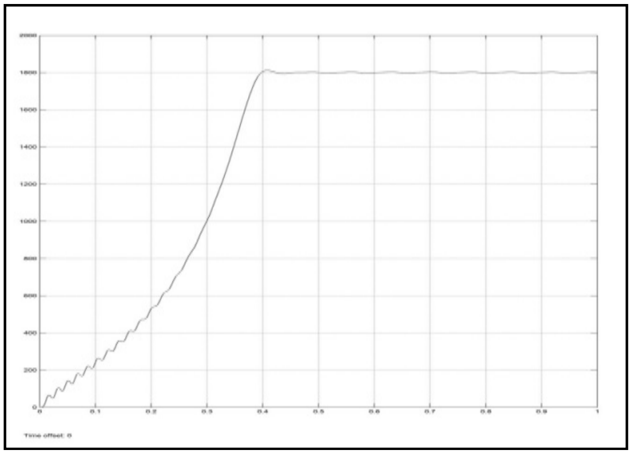

Figure 10: Speed characteristics of IM drive

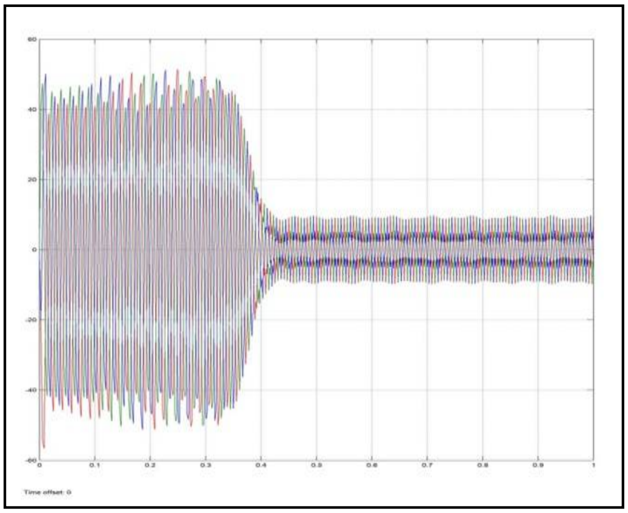

Figure 11: Output current of IM drive

Figure 9 shows the torque characteristics of the induction motor. We can see slight fluctuations in the characteristics. Figure 10 shows the speed characteristics of the induction motor. We can see that speed reaches 1800 rpm, the motor rated speed. Figure11 shows the output currents of the motor. Red color indicates i_a, green color indicates i_b and blue color indicates i_c. We can see that the starting current is reduced when the motor reaches its rated speed.

7. Conclusion

Modeling and simulation of induction motor was carried out using state space model equations. Fuzzy logic controller shows fast control response with three-phase induction motor. Two different control techniques are usually used with Fuzzy logic controller which is scalar and vector control techniques. The vector control has better response as compared to scalar control. As it is apparent from the speed curve, the fuzzy controller drastically decreases the rise time. The frequency of firing signals changes as per the controller output, thus increasing the magnitude of applied voltage to Induction Motor thus changing the speed

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