

PERFORMANCE ANALYSIS OF FUZZY BASED FIELD ORIENTED CONTROL OF INDUCTION MOTOR DRIVES FOR HYBRID ELECTRIC VEHICLES

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ABSTRACT

Induction motors (IMs) have widely been regarded as one of the most suitable options in automotive industry for electric propulsion systems of hybrid electric vehicles (HEVs) due to their reliability, ruggedness and low cost. In the past, poor dynamic response of IMs was a key constraint that limited their capability in applications that require speed tracking and fast positioning. However, the development of field oriented control made it possible to decouple the stator current into flux and torque producing components, enabling an independent command on the motor torque for a simpler, more accurate speed control. Design of a field oriented controller requires the knowledge of the phase angle of rotor flux. Indirect field oriented control (IFOC) is a method to determine this phase angle by estimation which eliminates the requirement of additional sensors. However this estimation increases the complexity and the computation time of the control system. Fuzzy logic offers an alternative technique to design such a control system by making decisions based on human expertise, thus avoiding complex calculations. This paper describes the implementation of IFOC using both a conventional PI as well as a fuzzy based controller to compare their performance. Since a fuzzy based control does not depend on machine equations and performs on the basis of linguistic if-else decisions, it produces a faster speed response. Moreover, the torque and speed oscillations were observed to be much lower, as desired in an HEV drive train.

KEYWORDS: Fuzzy logic, Hybrid Electric Vehicle, Indirect field oriented control, Induction motor drive, Performance analysis.

I. NOMENCLATURE

L_m	:Mutual inductance
L_r	:Rotor inductance
L_{rr}	:Rotor leakage inductance
R_r	:Rotor resistance
R_s	:Stator resistance
ω_s	:Synchronous speed
ω_r	:Rotor speed
ψ_{qs}	:q-axis stator flux
ψ_{ds}	:d-axis stator flux
ψ_{qr}	:q-axis rotor flux
ψ_{dr}	:d-axis rotor flux
i_{qs}	:q-axis stator current
i_{ds}	:d-axis stator current
i_{qr}	:q-axis rotor current
i_{dr}	:d-axis rotor current

II. INTRODUCTION

The performance of a hybrid electric vehicle (HEV) depends on the behavior of its electric propulsion system that consists of a traction motor and its electrical drive. Selection of an appropriate motor plays a crucial role in the performance of the HEV drive train and is an on-going topic of research in the automotive industry. The traction motor drive should offer wide speed ranges, high power, fast torque

response, reliability under harsh operating conditions of the motor along with low cost and maintenance for market acceptability [Zeraoulia and Diallo]. Among the electric motors present in the market, permanent magnet (PM) synchronous motors, switch reluctance motors (SRMs) and induction motors (IMs) are possible candidates since they exhibit the characteristics desired in traction applications in hybrid vehicles. PM synchronous motors have high power density, low torque ripples, and are easy to control but their high cost and low efficiency at extended speed ranges creates a disadvantage [Williamson *et al*]. Similarly, drawbacks of SRMs include high acoustic and electromagnetic interference (EMI) noise; torque ripples and need for a special inverter topology. Induction motors are suitable for HEVs due to their low cost, simple construction, minimum maintenance requirement and low weight. They are extremely reliable and rugged making them well suited for severe operating environment of HEV traction. They can be rated for higher power levels with low acoustic noise and can achieve a wide speed range operation beyond base speed through flux weakening. IMs have been used in various industrial applications for a long period of time. This is why in terms of design, manufacture and control technique induction motors are the most mature. Although previous methods displayed poor dynamic response, vector control also known as field oriented control (FOC) of induction machines has enabled the decoupling of stator current into torque and flux producing components that gives independent control over the motor torque while maintaining a constant flux that enables an accurate and precise IM control. FOC is based on the knowledge of the phase angle of rotor flux. In case of direct FOC this field angle is measured using flux sensors or calculated from terminal voltage. To remove this requirement of sensors, which adds to the cost of the machine, indirect field oriented control was suggested where the field angle is estimated using slip speed.

Although vector control has been successfully implemented using PI compensation, the need to reduce the computation time of such control problems is desired for faster response. Fuzzy logic offers a substitute method to design a control algorithm derived from human intelligence of how the system should respond for any given input. This paper will demonstrate the improvement in the motor drive performance by using fuzzy based control system to implement IFOC.

III. INDIRECT FIELD ORIENTED CONTROL OF INDUCTION MOTORS

Scalar control strategies for induction motors exhibit a poor dynamic response [Bousserhane *et al*]. This is explained by the deviation of air-gap flux linkage from set value in both magnitude and phase. Since scalar techniques control the magnitude and frequency of the stator current and have no command over the phase angle, the motor responds with high torque and speed oscillations. In recent years, development of field oriented control has opened the possibility of using AC motors for precision control [Lin and Liaw]. FOC allows the stator current to be decoupled into torque producing and flux producing components that can be controlled and maintained independent of each other, making the control much similar to that of a separately excited DC motor. FOC is based on the assumption that the position of the rotor flux linkage ψ_r is at an angle θ_f from the stationary reference frame as shown in Fig.1 [Krishnan].

Assuming ψ_r to be on the d-axis of the synchronously rotating frame, the stator current can be resolved into a field producing component i_{ds} in phase with ψ_r , and a perpendicular, torque producing current component i_{qs} . The rotor voltage equations of the induction motor in the synchronous reference frame are given below.

$$\left. \begin{aligned} v_{dr} &= R_r i_{dr} - (\omega_s - \omega_r) \psi_{qr} + \frac{d\psi_{dr}}{dt} \\ v_{qr} &= R_r i_{qr} + (\omega_s - \omega_r) \psi_{dr} + \frac{d\psi_{qr}}{dt} \end{aligned} \right\} \quad (1)$$

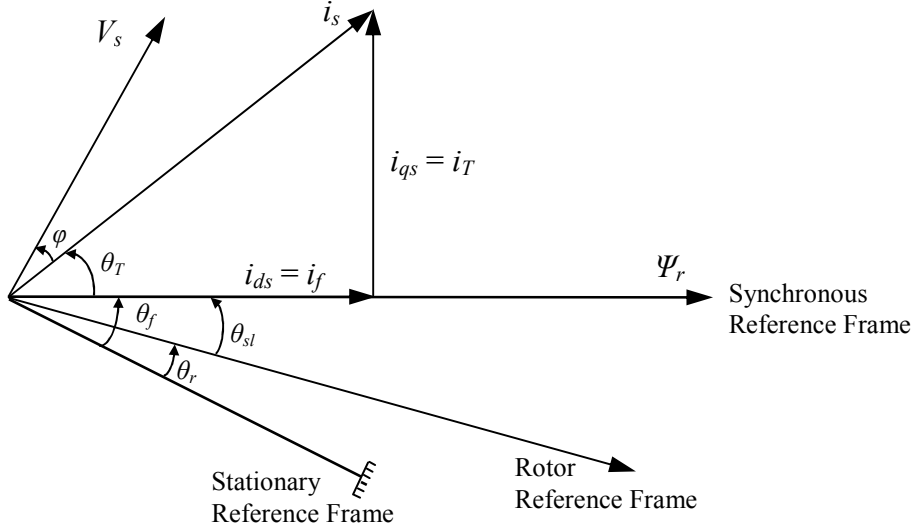


Fig.1. Phasor diagram of field oriented control.

The slip speed is defined as

$$\omega_{sl} = \omega_s - \omega_r \quad (2)$$

For a squirrel cage induction motor, the d and q axis rotor voltages are zero. Hence (1) becomes

$$\left. \begin{aligned} 0 &= R_r i_{dr} - \omega_{sl} \psi_{qr} + \frac{d\psi_{dr}}{dt} \\ 0 &= R_r i_{qr} + \omega_{sl} \psi_{dr} + \frac{d\psi_{qr}}{dt} \end{aligned} \right\} \quad (3)$$

Rotor flux linkages of IM are given as:

$$\left. \begin{aligned} \psi_{dr} &= L_m i_{ds} + (L_{rr} + L_m) i_{dr} = L_m i_{ds} + L_r i_{dr} \\ \psi_{qr} &= L_m i_{qs} + (L_{rr} + L_m) i_{qr} = L_m i_{qs} + L_r i_{qr} \end{aligned} \right\} \quad (4)$$

If the rotor flux ψ_r lies on d-axis of the synchronous frame

$$\left. \begin{aligned} \psi_{dr} &= \psi_r \\ \psi_{qr} &= 0 \end{aligned} \right\} \quad (5)$$

Applying (5) to (3), the rotor voltage equations become:

$$\left. \begin{aligned} R_r i_{dr} + \frac{d\psi_r}{dt} &= 0 \\ R_r i_{qr} + \omega_{sl} \psi_r &= 0 \end{aligned} \right\} \quad (6)$$

Rotor currents can be derived from the flux linkage equations by substituting (5) in (4):

$$\left. \begin{aligned} i_{qr} &= -\frac{L_m}{L_r} i_{qs} \\ i_{dr} &= \frac{\psi_r}{L_r} - \frac{L_m}{L_r} i_{ds} \end{aligned} \right\} \quad (7)$$

Solving (6) and (7), the q and d axis stator currents are given as:

$$\left. \begin{aligned} i_T = i_{qs} &= \omega_{sl} \frac{L_r \psi_r}{R_r L_m} \\ i_f = i_{ds} &= \frac{1}{L_m} \left[\psi_r + \frac{L_r}{R_r} \left(\frac{d\psi_r}{dt} \right) \right] \end{aligned} \right\} \quad (8)$$

Since the current component responsible for generating field must be in phase with the rotor flux, the d-axis stator current is established as i_f . Hence the perpendicular component i_{qs} must be the torque producing factor and is named i_T .

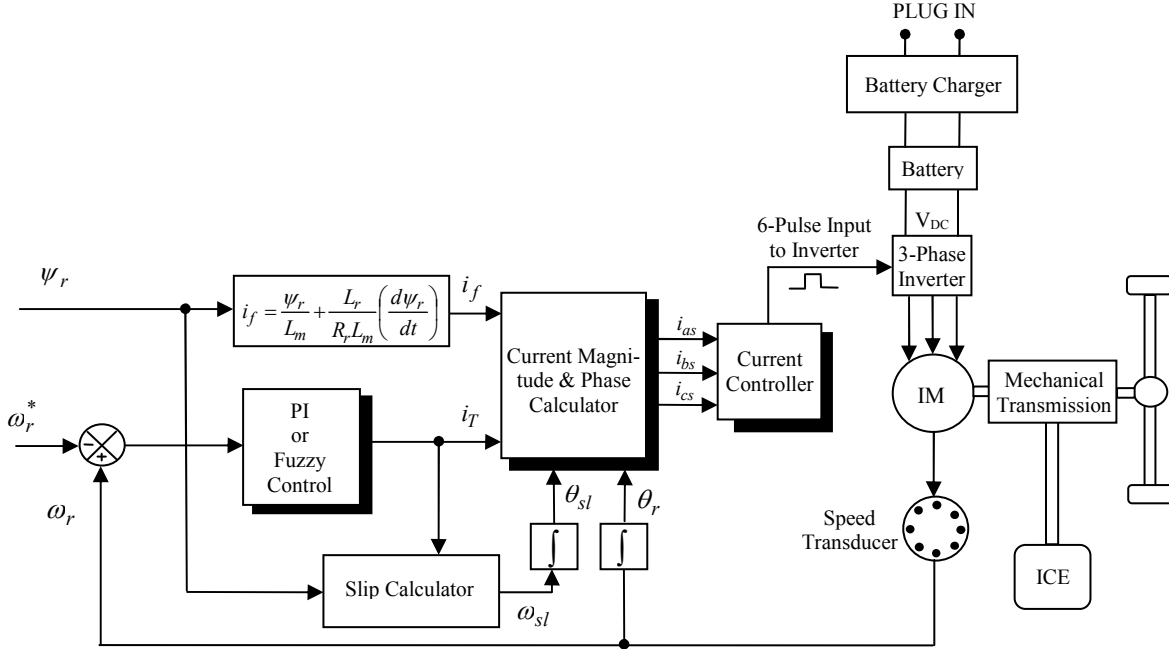


Fig.2. IFOC of induction motor drive in plug-in HEV application.

Fig.2 shows the indirect vector control scheme of induction motor. A transducer sends the rotor speed signal to a conventional PI controller that generates a torque command based on the deviation from set speed [Liaw *et al*]. This torque command is used to calculate the current component i_T .

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \quad (9)$$

Within the normal range of operation, flux can be kept constant producing a constant field component i_f [Wijesundera and Jackson]. The field and torque producing components determine the magnitude of the stator current.

$$i_s = \sqrt{i_f^2 + i_T^2} \quad (10)$$

Phase of the current signal is the sum of θ_f and θ_T where

$$\theta_T = \tan^{-1}(i_T / i_f) \quad (11)$$

The field angle is the sum of slip angle θ_{sl} and rotor angle θ_r that are obtained by the integration of slip speed and rotor speed respectively. The stator current magnitude and phase angle are sent to a current controller that determines the 3-phase current signal and generates pulses to drive the PWM inverter. PI is one of the most commonly used control methods due to its simplicity. It depends on the tuning of its

proportional gain K_p and integral gain K_i which can be adjusted through trials to give optimum response. The PI compensation is given by the equation below.

$$G_c(s) = K_p + \frac{K_i}{s} \quad (12)$$

Increase in K_p reduces error and rise time whereas higher K_i values reduce oscillations but increase settling time. Although this control method is reliable and has been in use extensively for control systems application, however, it lacks the ability of efficient tracking and regulation simultaneously. Moreover, the complex computation of the IFOC technique and parameter sensitivity is also a concern. The slip speed is calculated using i_T which is a function of rotor resistance. In a hybrid vehicle this resistance is expected to increase as the engine heats up, resulting in deviation from set speed.

IV. FUZZY BASED FIELD ORIENTED CONTROL

Fuzzy logic offers a linguistic approach to develop control algorithms for any system. It maps the input-output relationship based on human expertise and hence, does not require an accurate mathematical model of the system. This consequently makes the fuzzy control tolerant to parameter variation. Moreover, the nonlinearities that are generally difficult to model or are ignored altogether to reduce complexity are accounted for in a fuzzy control system, making it more accurate and robust.

Fig.3 shows the fuzzy control scheme for IFOC. The controller accepts two inputs, error e between the reference speed and rotor speed; and the rate of change of error \dot{e} . Both inputs are mapped on fuzzy sets with a universe of discourse ranging from -360 to 360. Fuzzy sets for each input consist of 7 membership functions from negative large (NL), negative medium (NM), negative small (NS), zero (ZO) upto positive large (PL). Similarly the output has a universe of discourse from -1 to 1. Gain G_{in} is tuned to map the acceleration to the given range of fuzzy sets and G_{out} is tuned to scale the controller output to a corresponding value of i_T required to control the motor.

The fuzzified inputs are received by the rule base that generates the consequent value for change in current signal, Δi_T , based on the specified *if-else* rules. The rule base determines the weight of each membership function for the inputs and triggers the corresponding rules. For example if both e and \dot{e} are NL it implies that the rotor speed is very low and it is further decelerating, hence Δi_T is set to PL to increase the value of q-axis stator current. On the other hand if e is ZO and \dot{e} is PL it suggests that although the rotor has achieved desired speed, it will continue to accelerate and is expected to overshoot, so i_T is reduced by setting Δi_T to NL. Thus it is possible to predict the extent of speed deviation expected from the motor in the successive time steps. The entire rule base is hence designed based on human perception as to how much the current must increase or decrease depending on the speed and as well as the acceleration of the motor to reduce the deviation around the reference signal. Once the rule base is designed, it can be refined for accurate results through trials.

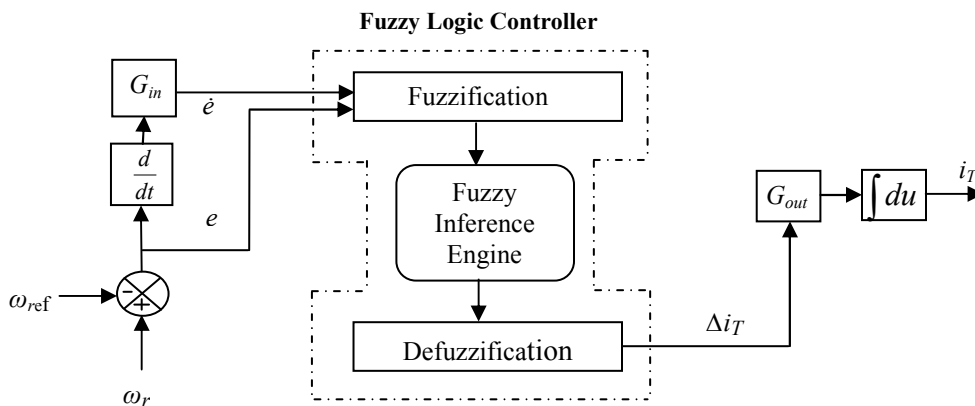


Fig.3. Block diagram of fuzzy controller.

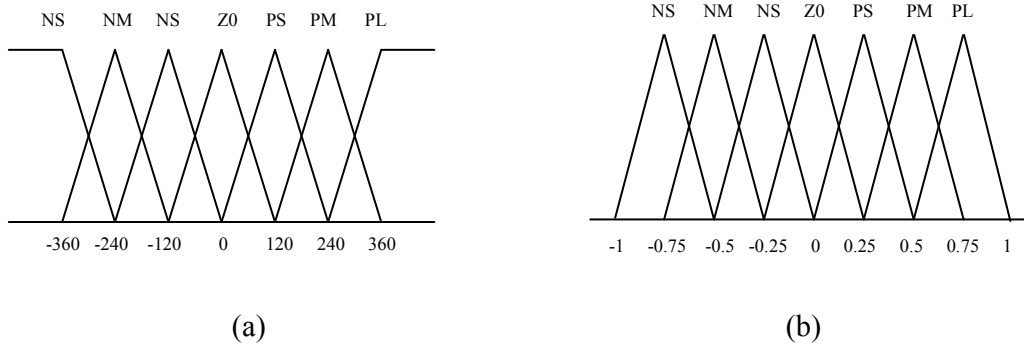
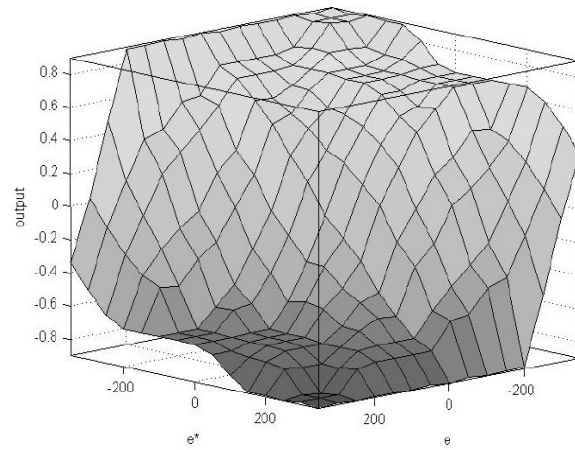


Fig.4. (a) Input membership functions, (b) Output membership functions.

$\begin{matrix} e \\ \dot{e} \end{matrix}$	NL	NM	NS	ZO	PS	PM	PL
NL	PL	PL	PL	PL	PL	PL	NS
NM	PL	PL	PM	PM	PS	ZO	NM
NS	PL	PM	PS	PS	NS	NM	NM
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PM	PM	PS	NS	NM	NM	NL
PM	PM	ZO	NS	NM	NM	NL	NL
PL	PS	NL	NL	NL	NL	NL	NL



(a) (b)

Fig.5. (a) Fuzzy rule base, (b) 3D surface view of the fuzzy rule base.

The net weight of the output current is computed from the triggered membership functions using Min aggregation method. The weighted output is transformed into required current signal through defuzzification. This is accomplished by the inverse transformation to map the calculated output from the fuzzy domain to a crisp real-time value. The conventional method of defuzzification is the centre of area (COA), which calculates the centre of the area representing the output fuzzy term. The output u of the controller is given by:

$$u = \frac{\int \mu(x_i) x_i du}{\int \mu(x_i) du} \quad (13)$$

where x_i is a point in the universe of discourse and $\mu(x_i)$ is its membership value in the membership function.

Since the effective output from the fuzzy controller is the amount of increment or decrement in current signal, Δi_T , it is integrated to generate the net value for the torque producing current component i_T [Heber]. This fuzzy based control algorithm was implemented in the Fuzzy Toolbox of Matlab/Simulink. The toolbox allows the user to create multiple inputs and outputs, define the rule base in linguistic terms in the Rule Base Editor and is also capable of displaying which rules are triggered for any given set of inputs to indicate the consequent output generated.

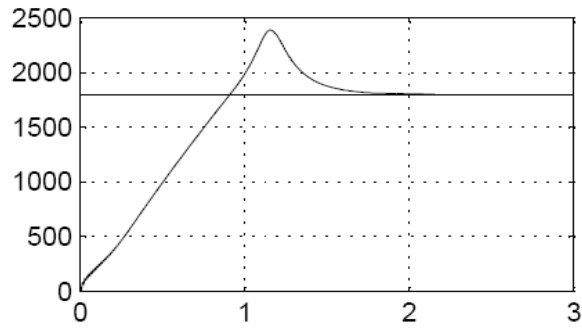
Conventional PI control has the limitation of being one dimensional. Fuzzy controller, on the other hand, can have multiple inputs and multiple outputs. The inputs of the system described above not only help to determine the net error but also predict how fast the error is changing, enabling the controller to give a better response in time, thus ensuring smaller overshoots. It can be seen that the fuzzy controller is independent of any motor parameters and does not require machine equations making the control more robust.

V. SIMULATION RESULTS

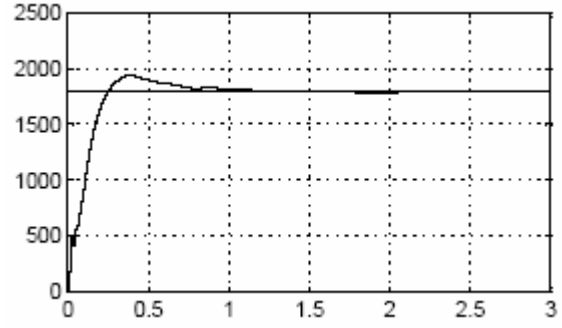
Field oriented control design for induction motor was implemented in MATLAB/Simulink. Fig.6 shows the tracking performance of PI control for a 3 phase, 2 Pole, 37kW squirrel cage induction motor under no load. Given a reference speed of 1800 rpm, the PI controller takes approximately 1.65 seconds to reach steady state. The speed overshoots by 500 rpm before attaining set speed. This overshoot can be decreased by reducing the value of K_i , but the resulting response will have higher oscillations. This is why the tuning of gain values in the PI controller is a trade-off between higher oscillation and higher overshoot with delayed response. Performance of the fuzzy controller for the same reference signal under no load is shown in Fig. 7. The fuzzy based control was able to reach set speed in 1 second with a very small overshoot. For real-time speed tracking, this fast response of fuzzy controller can ensure rapid acceleration of the vehicle in short duration.

For the PI control, the high current oscillations sustain for 1.2 seconds which consequently results in oscillation of the electromagnetic torque T_e . These high torque oscillations produce fatigue on vehicle components and vibrations during the drive that are undesirable for passengers. For the fuzzy controller, on the other hand, current oscillations reach the steady state value in 0.4 seconds which is transferred into reduced torque oscillations, ensuring that the motor runs smoothly.

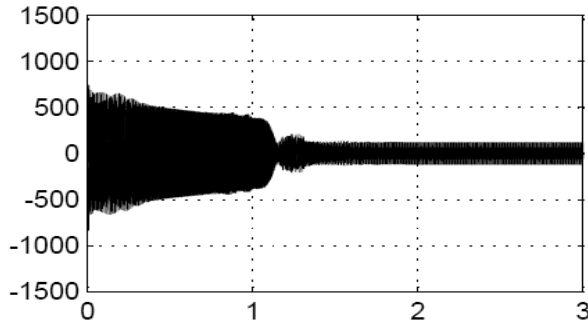
Research is currently in progress to determine the behaviour of fuzzy controller under applied load changes and parameter variations. The aim is to apply a change in the loading condition while motor is operating in steady state. Under the operating conditions of the vehicle, due to higher temperatures, rotor resistance of the induction machine is susceptible to change. Response of the fuzzy based control system will be analysed for this change in rotor resistance. These results will be compared with the response of the PI controller for the same parametric changes. It is expected that fuzzy controller will have smaller deviation from set speed under change in loading condition and parameter variation since it is independent of machine equations. To observe the performance of the fuzzy based control in real-time speed tracking, the above mentioned technique will be implemented on an experimental setup consisting of a vector control based induction motor drive. These experiments are expected to verify the simulated results.



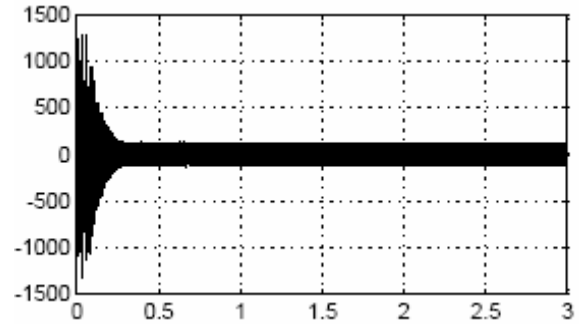
(a)



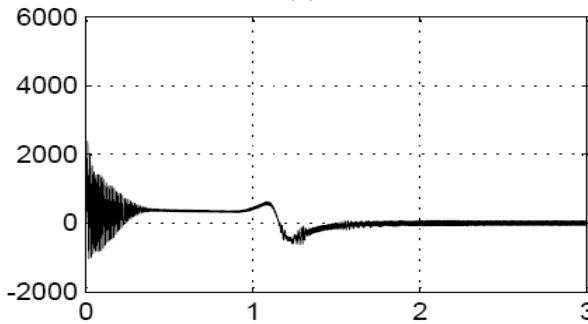
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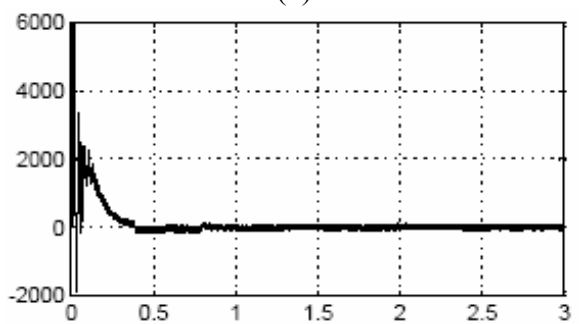
(b)



(b)



(c)



(c)

Fig.6. Rotor speed (rpm), (b) Stator current (A) and (c) Electromagnetic Torque (Nm) for PI control.

Fig.7. Rotor speed (rpm), (b) Stator current (A) and (c) Electromagnetic Torque (Nm) for fuzzy control.

VI. CONCLUSION

The performance of fuzzy based IFOC for HEVs in comparison to a PI control has been demonstrated in this paper. From the simulation results it is clear that fuzzy based algorithm is an efficient substitute control methodology that gives faster response with lower speed deviation to ensure rapid acceleration and smooth drive in automobiles. Lower torque and current oscillations help limit the stresses on the motor as well as the rest of the mechanical components of the vehicle. PI control requires trial and error for tuning of its proportional and integral gain, whereas fuzzy controller is tuned by intelligent perception. Since the rule base and membership functions are identified in linguistic terms, they are easier to comprehend, design and tune. Using rate of change of error as an input helps in predicting how much the error is expected to reduce or increase in the next time cycle. This allows the controller to make an intelligent response ahead of time without letting the speed deviate to a large extent. Moreover

the control algorithm is independent of machine equations, making the computation faster and less intricate.

VII. ACKNOWLEDGEMENT

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