Implementation of an Intelligent Controller for Three Phase Vector Controlled Induction Motor Drive

Madhusudan Singh¹  Mini Sreejeth¹  Shoaib Hussain¹

Abstract—Induction motor (IM) control has drawn considerable attention in the past decade due to its wide range of application in industry. Vector control allows a decoupled control of electromagnetic torque and the motor flux. In this paper an intelligent control scheme for a three phase vector controlled induction motor drive is implemented using Fuzzy Logic Controller (FLC) and the performance is compared with conventional PI Controller. The rule base of FLC is designed using the speed error and the change in error, which are the two linguistic variables. An FLC embodies human like decision to compensate for uncertainty in parameter variation and non-availability of data. The vector control scheme of the IM drive incorporating PI-Controller and FLC is experimentally implemented using a digital signal processor board DS-1104 in the laboratory on a 3hp Induction Motor. A comparison of the drive performance using conventional and an intelligent controller is presented through simulation studies as well as through real time implementation of the scheme. The objective of the intelligent controller is to maintain the drive speed to the reference speed and enable the drive to provide a fast dynamic performance with smaller tracking error, while controlling the nonlinear dynamics of IM.

Keywords—Field oriented control (FOC), fuzzy logic controller (FLC), indirect vector control, intelligent controller, PI controller

I. INTRODUCTION

The rugged construction, minimal maintenance and low cost of the IM Drive has resulted in its numerous industrial applications and has also drawn attention of researchers to explore options for better speed and torque control of IM [1, 2]. The IM drives are replacing DC motors and other drive systems due to their low cost and high performance [3, 4]. For the operation of IM as an adjustable speed drive, it is necessary to decouple the stator current of IM into flux and torque current components [1] and control them independently to achieve fast dynamic response, similar to a separately excited DC motor. This is achieved by vector control techniques. In an indirect vector controlled induction motor (IVCIM) drive, the three phase current vectors from a stationary reference frame are converted to a two dimensional rotating reference frame, where the d and q axes components of the stator currents represent the independently controllable flux and torque producing components [5, 6]. The need for separate excitation resulted in intelligent control methods like Fuzzy [7], Neural Network [8, 9, 10] based techniques being researched.

In this paper a novel intelligent control scheme for a three phase vector controlled IM drive is implemented using Fuzzy Logic Controller (FLC) and the performance is compared with conventional PI Controller. The proposed scheme is analyzed through simulation studies and experimental validation using PI and FLC speed controllers for a 3hp laboratory IM. A voltage source inverter (VSI) and a digital signal processor board DS-1104 are used to develop the IVCIM drive. A comparison of the drive performance under different operating conditions such as starting, sudden change in load, speed reversal etc. using conventional and intelligent controllers is presented through simulation studies as well as through real time implementation of the scheme. This paper is organized into five more Sections, with Dynamics of IVCIM, Speed Controllers, Simulation Results, Experimental Evaluation of IVCIM and Conclusion presented in Sections II, III, IV, V and VI respectively.

II. DYNAMICS OF IVCIM

The dynamic model of an IM involves transforming the three phase line currents using Park’s Transformation [1] into two independently controllable orthogonal DC quantities, direct axis current, \( i_{ds} \) and quadrature axis current \( i_{qs} \), to control the flux and torque/speed of the IM independently. In the synchronously rotating d-q reference frame, the electromagnetic torque developed by the IM, \( T_e \) is given by [11, 12]

\[
T_e = \frac{3 P L_m}{2 L_r} (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})
\]  

(1)

where \( P \) is the number of poles, \( L_r \) and \( L_m \) are the rotor and mutual inductances, \( \psi_{dr} \) and \( \psi_{qr} \) are \( d \) and \( q \) axes rotor flux linkages respectively. In the synchronously rotating frame, as the \( d \) axis is aligned with the rotor flux, \( \psi_{dr} = \psi_r \) and \( \psi_{qr} = 0 \), accordingly:

\[
T_e = \frac{3 P L_m}{2 L_r} \psi_{dr} i_{qs}
\]  

(2)

\[
\omega_{sl} = \frac{L_m}{L_r} \frac{i_{qs}}{\psi_{dr}} r_r
\]  

(3)

where \( r_r \) is the rotor resistance. The dynamic and steady state behaviour of the rotor flux is expressed as (4) and (5)

\[
\frac{d\psi_{dr}}{dt} + \frac{r_r}{L_r} \psi_{dr} = \frac{r_r L_m}{L_r} i_{ds}
\]  

(4)

\[
\psi_{dr} = L_m i_{ds}, \omega_{sl} = \frac{r_r}{L_r} \frac{i_{qs}}{i_{ds}}
\]  

(5)

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The \( d \)-axis stator current is controlled to maintain the flux at its rated value and the \( q \)-axis stator current is varied to achieve the desired electromagnetic torque. In Indirect Vector Control method, the rotor angle \( \theta \) is evaluated in a feed forward manner using the measured speed \( \omega_r \) and the slip speed \( \omega_{sl} \) as:

\[
\theta = \int (\omega_r + \omega_{sl}) \, dt
\]

The speed error is converted into a torque producing current component \( i_{ds}^{'*} \), using any conventional/intelligent controller. Fig.1 shows the block diagram of IVCIM, where torque is controlled by PI controller or Fuzzy Logic controller. The flux producing component of the stator current \( i_{qs} \), as given in (5) is constant up to the rated speed of operation, beyond which it is controlled by weakening the flux. These \( d \) and \( q \) axes components of stator current, \( i_{ds} \) and \( i_{qs} \) are transformed into three phase reference currents. A hysteresis PWM Current Controller compares the reference currents with actual sensed stator currents and generate necessary PWM signal for gating of VSI [13]. The variable frequency, variable voltage inverter output when applied to the stator windings of the IM tracks the commanded speed.

![Fig.1: Block Diagram of Indirect Vector Controlled Induction Motor](image)

III. SPEED CONTROLLERS

A. PI controller

PI controller is a conventional control technique used in most of the control process applications. The input to the PI controller, \( e \) is the difference between the reference speed \( \omega_r^* \), and the actual speed \( \omega_r \). The output and input relationship of a PI speed controller is described as

\[
e_0 = K_p (e) + K_i \int e \, dt
\]

The values of the parameters \( K_p \) and \( K_i \) are determined to meet the desired dynamic response of the IVCIM.

B. Fuzzy logic controller (FLC)

The general scheme of FLC for the speed control of IM [14] is shown in Fig. 2. The two inputs to the FLC are the speed error \( e \), and the rate of change of speed error \( ce \), which are calculated at every sampling time, \( t_s \)

\[
e(t_s) = \omega_r^* (t_s) - \omega_r (t_s)
\]

The FLC output \( \Delta i_{qs}^* \) , for the IVCIM is given by

\[
\Delta i_{qs}^* = e \cdot GE + ce \cdot GCE
\]

A typical FLC architecture composes of an inference engine and a defuzzifier. The inference engine processes the inputs using the knowledge base. The outputs of the inference engine are converted into crisp values by the defuzzifier. Designing of a FLC involves 1) identifying the range of the controller inputs and outputs, 2) creating fuzzy sets for each input and output, 3) translating the interaction of the input and outputs into if-then rules and creating the rule matrix, 4) deciding on the inference engine and the defuzzifier and then applying them to crisp inputs to produce crisp outputs and 5) implementation of controller, testing it and modifying it, if necessary. The fuzzification maps the error and change in error to linguistic labels of fuzzy sets. A Sugeno type Fuzzy Logic Controller is designed for the IVCIM, the inputs, i.e. the error \( e \), change in error \( ce \) and the output \( \Delta i_{qs}^* \) follow the membership function plot as shown in Fig. 3.

![Fig.2: Block diagram of fuzzy Logic based controller](image)

![Fig.3: Sugeno membership function plots for (a) Inputs (b) Output](image)
processed by the inference mechanism that executes $7 \times 7$ rules [14, 15] represented in rule base shown in Table 1, where the linguistic levels NB, NM, NS, Z, PS, PM and PB denote negative big, negative medium, negative small, zero, positive small, positive medium and positive big respectively. The output of the fuzzy controller is directly computed from $e$ and $ce$.

<table>
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<tr>
<th>$c$</th>
<th>NB</th>
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The following rules are formed as shown in Table 1.

- if $e$ is $Z$ and $ce$ is $Z$, then $\Delta i_q$ is $Z$
- if $e$ is $PS$ and $ce$ is $Z$, then $\Delta i_q$ is $PS$
- if $e$ is $NS$ and $ce$ is $Z$, then $\Delta i_q$ is $NS$

Similarly other rules are also formed for all combinations of $e$ and $ce$ and summarized in Table 1. Each of the inputs and output contain membership function with all these seven linguistics as shown in Fig. 3(a).

**IV. SIMULATION RESULTS**

Simulation study of the IVCIM is performed in MATLAB to analyze the dynamic behavior of the drive before actually developing an experimental setup. The dynamic behaviour of a three phase 3hp, 230 V, 1440 rpm IM is analysed through simulation studies using both PI and FLC speed controllers. The tuning of PI and FLC controllers are carried out through simulation study to determine the necessary tuning parameters. The rating of the IM and controller parameters are given at Appendix.

**A. Performance of IVCIM using PI controller**

The performance analysis of IVCIM using a classical PI controller is described under different operating conditions. The simulation results during starting of IVCIM drive is shown in Fig.4.

At starting the drive develops starting torque of about 20Nm to track the desired no-load speed of 150 rad/sec. It is observed that the motor reaches the rated speed in just over 0.03 sec with an offset in speed of 2 rad/sec. The starting current is initially higher and reaches a steady state at 2.7A. As soon as the drive attains the desired no-load speed, the torque is reduced and the motor current decreases to the level of no-load current. At $t=0.4$ sec a sudden load of 9Nm is applied to the motor shaft, which results in a small dip in the motor speed, which is finally regulated by the PI controller and the drive achieves the desired speed at $t=0.48$ sec. Due to the increase of load torque the stator current of the motor is increased. The PWM controller varies the output voltage instantaneously by changing the number of pulses and their widths during each alternation. The pulse width is decreased for lower rms voltages and increased for higher voltages. This variation of PWM line voltage waveform along with the torque is shown in Fig. 4.

**B. Performance of IVCIM using FLC**

The performance analysis of IVCIM using FLC is shown in Fig. 5. At no-load, it is observed that the speed transition from zero to rated speed takes place in 0.03 sec with no offset. The starting current is initially higher and eventually reduces to steady state of 2.7A. When a load of 9 Nm is suddenly applied at $t=0.1$ sec, there is a momentary dip in speed which is recovered in just 0.05 sec and the motor once again settles at the rated speed of 150 rad/sec with a proportional increase in stator current. The torque pulsations in case of FLC based IVCIM are less as compared to that of PI controller, implying smoother operation of the motor having same value of hysteresis band. Being a nonlinear controller, FLC models the nonlinear dynamics of IVCIM drive accurately to provide fast dynamic response of the drive under different operating conditions.

**V. EXPERIMENTAL EVALUATION OF IVCIM**

The experimental setup used for the laboratory prototype is shown in Fig.6, which includes a three phase 3hp squirrel cage IM fed by a VSI. The IM is coupled to a DC generator, which act as the load. A dSPACE Controller whose software operates under Matlab/Simulink environment is used for generating PWM signals to the VSI. The current sensors sense the line currents $i_a$ and $i_b$ from the motor. The voltage sensor provides the speed.
equivalent voltage from the tacho-generator. These sensed signals are fed to the Analogue to Digital (ADC) terminals of the dSPACE controller and MATLAB/Control Desk where the control scheme is implemented using ‘RTI’ block sets for interfacing MATLAB with DS-1104. The pulses generated from the MATLAB/Simulink model are fed to the VSI through the Digital I/O connector port of the dSPACE controller.

A. Experimental evaluation of IVCIM using PI controller

The experimental performance characteristics of IVCIM is obtained under different operating condition and test results are shown in Fig. 7. The IM is started at no load for a commanded speed of 150 rad/sec. The profile of the motor current has initial high starting current surge, which eventually settles to the steady state current in about 1.5 sec. At t=10 sec, a load torque of 7Nm is applied at the motor shaft, which increases the motor current to 7.5A with a momentary dip in the motor speed. However the PI controller regulates the speed of motor to 150 rad/sec within 2 sec.

The performance of PI controller in regulating the motor speed in forward, reverse motoring mode and braking mode is shown in Fig. 8. Initially the motor is operated in braking mode for 3 secs followed by forward mode at 150 rad/sec upto t=6.5 sec and then in reverse motoring mode at -150 rad/sec upto t=10.5 sec. The motor is then operated at -100 rad/sec upto t=14 sec and then finally at 100rad/sec.

The performance of IVCIM is dependent on the hysteresis current controller. A change in hysteresis band changes the switching frequency of the IGBT. A higher value of hysteresis band is tried out experimentally using a PI controller and the performance of the IVCIM is shown in Fig.9. It is observed that speed and current take longer time to reach steady state.
B. Experimental Evaluation of IVCIM using FLC

Fig. 10 shows the experimental dynamic performance characteristics of IVCIM using FLC. When the motor is started for a commanded speed of 150 rad/sec at no-load, the performance of FLC is observed to be superior to that of PI controller as the motor takes just 2 sec to reach rated speed. After the initial high starting current, it settles down to a steady state value in about 1.2 sec. At t=4.2 sec, a load torque of 7 Nm is applied at the motor shaft, which increases the motor current proportionally with a momentary dip in the motor speed. However the Fuzzy Logic controller regulates the speed of motor to 150 rad/sec within 0.3 sec. The FLC regulates the current faster within desired range as compared to PI controller.

The current profile shows more harmonics in case of a PI controller. The FLC based IVCIM is able to reduce the harmonic content in the current. Also, less torque pulsations are observed in case of FLC based IVCIM as compared to PI controller based IVCIM validating the simulation results.

The motor took about 2 secs to track the commanded speed. The motor speed is then changed to forward motoring mode of 50 rad/sec at t=12.5 sec after which it is set to 150 rad/sec at t=18 sec. The motor tracks the commanded speeds in less than a sec. The speed regulation of motor in all the three modes improve significantly in case of FLC with reduced overshoots in speed as compared to PI controller.

Similar to PI controller, the IVCIM is operated with a higher value of hysteresis band using the FLC and the performance of the IVCIM is shown in Fig. 12. It is observed that speed and torque take longer time to reach steady state. The torque pulsations indicate that the motor current has significant harmonic content.

The torque pulsation in case of FLC based IVCIM are less as compared to that of PI Controller as evident from the simulation results shown in Figs. 4 and 5, which is also observed in case of experimental results as shown in Figs.7(c) and 10(c). Also, analysis of the simulation results shown in Figs. 4 and 5 reveal that the speed response is better while using FLC as compared to PI Controller, which is validated through experimental studies as shown in Figs. 7(b) and 10(b).
VI. CONCLUSIONS

In this paper an intelligent control scheme for a three phase vector controlled induction motor drive is implemented using FLC and the performance is compared with conventional PI Controller. The vector control scheme developed for the IM drive incorporating PI-Controller and FLC is experimentally implemented using a digital signal processor board DS-1104 in the laboratory on a 3 hp IM. A comparison of the drive performance under different operating conditions using conventional and intelligent controllers is presented through simulation studies as well as through real time implementation of the scheme. The IVICIM shows better speed response with FLC as compared to PI Controller. On application of sudden load, the FLC shows quicker response to reach steady state. The current profile is better in case of FLC, having reduced harmonic content. The performance of FLC in forward, reverse and braking mode is also observed to be satisfactory, resulting in quick and smoother transition of speed from forward motoring mode to plugging mode and to reverse motoring mode. Thus the results obtained experimentally and from simulation studies show superior performance of the drive with FLC.

APPENDIX

The parameters of PI and FLC controller, the rating of the 3 Phase Delta connected Squirrel Cage IM used for simulation and experimental studies are given in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Ratings of 3hp IM and Controller Parameters</th>
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<tr>
<td>Rated speed - 1440rpm</td>
</tr>
<tr>
<td>$R_s = 3.3 \Omega$</td>
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<tr>
<td>$L_s = L_r = 0.1573$ H</td>
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<tr>
<td>$P = 4$</td>
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<td>PI Controller: $K_p = 4$, $K_i = 3.5$</td>
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</table>

REFERENCES


BIographies

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