Performance Investigation of PID and Hybrid Controllers for Speed Control of Induction Motor using Direct Field Oriented (DFO) Control Technique

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ABSTRACT

In this work, we have done speed control of a direct field-oriented induction motor (DFOIM) using a PID plus fuzzy logic control (FLC) Technique. The reason behind the selection of PID because its parameter values can be chosen using a simple and useful rule of thumb. The FLC is developed based on the output of the PID controller, and the output of the FLC is the torque command of the DFCIM. The simulation has been carried out on a 0.14 hp induction motor and resulting waveforms are obtained under different stiff conditions to exhibit the effectiveness of the proposed controller and investigate the starting and transient performance of drive using a PID plus fuzzy logic control (FLC) scheme in MATLAB/SIMULINK environment. Moreover, the performance comparison between the PID controller and the hybrid (PID + Fuzzy) controller is also carried out. Index Terms: Direct Field oriented Induction motor (DFOIM), Induction motor, Fuzzy Logic Control (FLC), Performance Investigation etc.

INTRODUCTION

In recent years, field-oriented induction machine (FOIM) drives have been increasingly utilized in motion control applications due to easy implementation and low cost. Besides, they have the advantage of decoupling the torque and flux control, which is the desirable feature. However, the decoupling control feature can be adversely affected by load disturbances and parameter variations in the motor so that the variable-speed tracking performance of an IM is degraded. In general, both conventional PI and PID controllers have the difficulty in making the motor closely follow a reference speed trajectory under torque disturbances. To overcome this difficulty, an effective and robust speed controller design is needed.

Hence fuzzy-logic-based intelligent controllers have been proposed for speed control of FOIM drives. These intelligent controllers are associated with adaptive gains due to fuzzy inference and knowledge base. As a result, they can improve torque disturbance rejections in comparison with best trial-and-error PI or PID controllers. Nonetheless, no performance advantages of intelligent controllers in combination with a PI or PID controller are investigated.

Fuzzy control is a non-linear control and it permits the design of optimized non-linear controllers to improve the dynamic performance of conventional regulators. Due to the various advantages and applications, a hybrid PID plus fuzzy controller consisting of a PID controller and a fuzzy logic controller (FLC) in a serial arrangement for speed control of FOIM drives, more specifically, direct field-oriented IM (DFOIM) drives is proposed. Moreover, a fuzzy logic controller is designed to carry out fuzzy tuning of the output of the PID controller to issue adequate torque commands.

MATHEMATICAL MODELING OF INDUCTION MOTOR

Equivalent Circuit Model

To analyze the operating and performance characteristics of an induction motor, an Equivalent Circuit can be drawn.
Fig.1: Equivalent circuit of one-phase out of three-phase of an induction motor

Let
\[ I_1 = \text{Stator current per phase} \]
\[ R_1 = \text{Stator winding resistance per phase} \]
\[ X_1 = \text{Stator winding reactance per phase} \]
\[ R_R \text{ and } R \text{ are the rotor winding resistance and reactance per phase, respectively} \]
\[ I_R = \text{Rotor current} \]
\[ V = \text{Applied voltage to the stator per phase} \]
\[ I_0 = I_m \text{ Magnetizing current} \]
\[ I_c = \text{Core-loss component of current} \]

Induced voltages
Let \( E_n \) be the induced voltage in the rotor at standstill:
\[ E_n = 4.44Nk \Phi_m f \]
Since \( f_r = f_e \) at standstill,
\[ E_{r0} = 4.44Nk \Phi_m f \]
\[ E_k = 4.44Nk \Phi_m f \]
\[ E_k = sE_{r0} \]

Rotor current
\[ I_k = \frac{E_k}{R_k + jX_k} = \frac{sE_{r0}}{R_k + sX_{r0}} \]
\[ I_k = \frac{E_{r0}}{R_k + jX_{r0}} \]

Transformation is done using the effective turns ratio, \( a_{eff} \) for currents
\[ I_1 = \frac{I_k}{a_{eff}} \]

Impedance transfer is made using the \( a_{eff}^2 \); where \( R_2 \) and \( X_2 \) are transferred values
\[ R_2 = a_{eff}^2 R_k \]

Phase impedance is given by
\[ Z_m = R_k + jX_k + \frac{jX_{r0} (R_k + jX_k)}{s + j(X_k + X_{r0})} \]

Now, phase current is given by
\[ I_1 = \frac{V}{Z_m} \]

Control structure of induction motor
The DFOIM drive is shown in Fig. 2.3. The dynamics of an induction motor can be described by synchronously rotating reference frame direct-quadrature (d-q) equations as:
\[
\begin{bmatrix}
    v_d & v_q \\
    \dot{i}_d & \dot{i}_q
\end{bmatrix} =
\begin{bmatrix}
    R_k + pL_s  & pL_s & pL_s & pL_s \\
    -qL_m & R_r + pL_r & -qL_m & pL_m \\
    pL_s & (q-\alpha)L_m & R_s + pL_s & (q-\alpha)L_m \\
    0 & -(q-\alpha)L_m & pL_m & (q-\alpha)L_m
\end{bmatrix}
\begin{bmatrix}
    \dot{v}_d \\
    \dot{v}_q \\
    \dot{i}_d \\
    \dot{i}_q
\end{bmatrix}
\]

where \( v_d, v_q, i_d, \text{ and } i_q \) are the d-axis and the q-axis stator voltages, stator currents and rotor currents respectively.
\( R_s, R_r, L_s, & L_r \) denote the resistances and self-inductances of the stator and the rotor respectively.
\( J_m, J_m \) denote the rotor and motor mechanical speeds.
\( N \) is the number of poles of the motor mechanical speed.
perform the alignment on a reference frame revolving with the space
mentioned strategies can be adopted:
- DFOC (Direct Field Oriented Control)
- IFOC (Indirect Field Oriented Control)

Considering the d-q model of the induction machine in the refer-
ted control equations (current model) requiring a rotor speed
control implies that the \( i_{ds} \) component of the stator current would
\( \perp \) \( i_{qs} \). This can be accomplished by choosing \( \omega_e \) as shown in Fig. 3.2 below:

\[ \tau = \frac{L_s}{R_s} \]
\[ \sigma = 1 - \frac{L_m^2}{L_s L_r} \]

To control the speed of the IM, the speed controller of the DFOIM
drive transforms the speed error signal \( e \) into an appropriate
electromagnetic torque command \( T_e^* \).

CONTROL TECHNIQUES

The speed of an induction machine can be controlled by adjust-
ing the magnitude and frequency of the applied stator voltages. The
specific control strategy implemented is dependent on the
requirements of the specific application. The two control tech-
niques can be categorized as below:
1. Scalar control
2. Vector control

Vector control techniques can be further divided into
a. Direct torque control
b. Field oriented control

* Field Oriented Control:

FOC involves controlling the components of the motor stator
currents, represented by a vector, in a rotating reference frame. In
the case of induction machines, the control is normally performed
in a reference frame aligned with the rotor flux space vector. To

\[ p \] stands for the differential operator \((\frac{d}{dt})\).
The notational superscript "s" stands for stationary reference
frame.

For a DFOIM drive, the flux has to fall entirely on d-axis. There-
therefore, the \( q \)-axis rotor flux \( \phi_{q_s} \) is set to zero. The controllers PI-1,
PI-2, and PI-3 are chosen to ensure that \( i_{ds} = \omega_e i_{qs} \), \( i_{qs} = i_{ds} \), and the flux command \( \phi_q \) and the estimated d-axis rotor flux \( \phi_{q_s} \) satisfies \( \phi_q = \phi_{q_s} \) respectively. The parameters \( \tau \) and \( \sigma \) are given by

\[ \tau = \frac{L_s}{R_s} \]
\[ \sigma = 1 - \frac{L_m^2}{L_s L_r} \]

\[ \text{Fig. 3: Phasor diagram describing the FOC scheme} \]

\[ \text{Fig. 4: Block diagram of FOC} \]

The block diagram of FOC as shown in Fig.3.3 has the follow-
ing blocks:
i. Flux Estimator

This block is used to estimate the motor's rotor flux. This cal-
culation is based on motor equation synthesis.

\[ \psi_r = \frac{L_m^2}{1 + T_s} (i_{ds}) \]
ii. \( \theta_f \) Calculation

This block is used to find the phase angle of the rotor flux rotating field using the following equations

\[
\theta_f = \theta_r + \theta_m \\
\frac{d\theta_f}{dt} = \frac{d\theta_r}{dt} + \frac{d\theta_m}{dt} \quad \text{... (18)}
\]

\[
\theta_f = \int (\omega_r - \omega_m) dt \quad \text{... (19)}
\]

\[
\omega_f = \frac{L_m i_m}{T_p \psi} \quad \text{... (20)}
\]

iii. Park Transformation

This block performs the translation of a, b & c phase variables into d-q components of the rotor flux rotating field reference frame.

![Park Transformation](image1)

\[
i_d = I_c \cos \theta + I_q \sin \theta \\
i_q = -I_c \cos \theta + I_q \sin \theta
\]

Fig. 5: Park Transformation

iv. Inverse Park Transformation

This block performs the conversion of the d-q component of the rotor flux rotating field reference frame into a, b and c phase variables.

![Inverse Park Transformation](image2)

\[
V_d = V_c \cos \theta - V_q \sin \theta \\
V_q = V_c \sin \theta + V_q \cos \theta
\]

Fig. 6: Inverse Park Transformation

v. \( i^{*}_q \) Calculation

This block uses the calculated rotor flux and the torque reference to compute the stator current quadrature component required to produce the electromagnetic torque on the motor's shaft.

vi. Flux PI

This block compares the estimated rotor flux and the reference rotor flux as the input to a Proportional Integrator which calculates the flux to be applied to the motor which in turn is used to compute the stator current direct component required to produce the required rotor flux in the machine.

THE HYBRID (PID + FUZZY) CONTROLLER

The hybrid (PID + Fuzzy) logic controller of the direct field oriented induction motor drive transforms the speed error signal into the electromagnetic torque command. The fuzzy system is built by graphical user interface tool provided by the fuzzy logic tool box in MATLAB environment system.

Fuzzy Inference System Editor for FLC

All the information for a given fuzzy inference system is contained in the FIS editor structure, including variable names, membership function etc. The fuzzy inference system editor firstly consists of the name of FIS file that can be imported from the workspace. In this system the FIS editor file for the FLC is named as "Fuzzy". The following important parameters related to fuzzy inference system of the FLC are shown:

- Name="Fuzzy"
- Type="mamdani"
- NumInputs=2
- NumOutputs=1
- NumRules=9

Membership Function Editor for FLC

The input membership functions used in the fuzzification process are \( \mu_{x_1}, \mu_{x_2}, \) and \( \mu_{x_3} \) to map a crisp input to a fuzzy set with a degree of certainty where \( X = g(t) \) or \( \Delta g(t) \) with \( g(t) = K_1 f(t) \) & \( \Delta g(t) = K_2 g(t) \). These three membership functions are chosen because of their simplicity for computation since a large number of membership functions and rules can cause high computational burden for a fuzzy controller. For any \( x \in N \), where \( N \) denotes the interval \( (-\infty, 0] \), its corresponding linguistic value is ‘N’. Moreover, for any \( x \in P \), where \( P \) denotes the interval \( (0, \infty) \), its corresponding linguistic value is ‘P’. For any \( x \in Z \), where \( Z \) denotes the interval \( [-b, b] \), its corresponding linguistic value is ‘Z’. The membership functions \( \mu_{x_1}, \mu_{x_2}, \) and \( \mu_{x_3} \) are given by
\[ \mu_1(x) = \begin{cases} 1 & x \leq -b \\ \frac{b-x}{b} & -b < x \leq 0 \\ 0 & \text{otherwise} \end{cases} \]  \quad \text{(21)}

\[ \mu_2(x) = \begin{cases} \frac{x+b}{b} & -b < x \leq 0 \\ \frac{b-x}{b} & 0 < x \leq b \\ 0 & \text{otherwise} \end{cases} \]  \quad \text{(22)}

\[ \mu_3(x) = \begin{cases} 1 & b \leq x \\ \frac{x}{b} & 0 < x \leq b \\ 0 & \text{otherwise} \end{cases} \]  \quad \text{(23)}

The fuzzy inference engine, based on the input fuzzy sets in combination with the expert's experience, uses adequate IF-THEN rules in the knowledge base to make decisions and produces an implied output fuzzy set \( u \).

i. If \( \Delta g(t) \in N \), then \( u(g(t), \Delta g(t)) = b \).

ii. If \( \Delta g(t) \in P \), then \( u(g(t), \Delta g(t)) = -b \).

iii. If \( \Delta g(t) \in Z \) and \( \Delta g(t) \in N \), then \( u(g(t), \Delta g(t)) = -b \).

iv. If \( \Delta g(t) \in Z \) and \( \Delta g(t) \in P \), then \( u(g(t), \Delta g(t)) = b \).

v. If \( \Delta g(t) \in Z \) and \( g(t) \in Z \), then \( u(g(t), \Delta g(t)) = 0 \).

Fig. 8 shows the structure of the hybrid (PID + Fuzzy) controller consisting of a PID controller and a fuzzy logic controller (FLC) in a serial arrangement for speed control of direct field oriented induction motor drive.

Table I shows the fuzzy rule base which are based on if-then rule.

<table>
<thead>
<tr>
<th>( u )</th>
<th>( g(t) )</th>
<th>( \Delta g(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta g(t) \in N )</td>
<td>( \Delta g(t) \in Z )</td>
<td>( \Delta g(t) \in P )</td>
</tr>
<tr>
<td>( g(t) \in N )</td>
<td>( b )</td>
<td>( b )</td>
</tr>
<tr>
<td>( g(t) \in Z )</td>
<td>( -b )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>( g(t) \in P )</td>
<td>( -b )</td>
<td>( -b )</td>
</tr>
</tbody>
</table>

Rule Editor of FLC

As there are two inputs each having three membership functions hence both inputs are combined using “AND” operator to form nine combinations of rule and these combinations are given to the output of rule editor named as “Fuzzy” which are shown in Fig. 10.
In the defuzzification process, ‘center of mass’ defuzzification method is used for transforming the implied output fuzzy set into a crisp output, and obtain

$$\Delta T^*_c(t) = \frac{\sum \sum \min \{\mu_i(g(t)), \mu_j(g(t))\} \times u(i, j)}{\sum \sum \mu_i(g(t)) \mu_j(g(t))}$$

Where

$$FL(a) = \begin{cases} (N, Z) & \text{if } a \in N \text{ and } a \in Z \\ (P, Z) & \text{if } a \in P \text{ and } a \in Z \\ (N) & \text{if } a \in N \text{ and } a \notin Z \\ (P) & \text{if } a \in P \text{ and } a \notin Z \end{cases}$$

The output of the fuzzy controller is given by

$$T^*_c = K_c \Delta T^*_c(t)$$

RESULTS AND DISCUSSIONS

The performance for the speed control of direct field oriented control induction motor using PID and hybrid (PID + Fuzzy) controllers are investigated through MATLAB simulation. The performance is analyzed for different cases. The results obtained are discussed along with the performance evaluation. In the first case the performance of PID controller is evaluated while for the second case the performance of a hybrid (PID plus Fuzzy) controller for speed control of Induction motor is evaluated. The command speed is increased from 0 to 900 rpm and a load disturbance of 1.1 N-m is suddenly applied to the shaft at 4.2 sec.

System Parameters

The system parameters of the 0.14 hp squirrel-cage induction motor used in this thesis are as following:

<table>
<thead>
<tr>
<th>Table I System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Parameters</td>
</tr>
<tr>
<td>Stator resistance</td>
</tr>
<tr>
<td>Rotor resistance</td>
</tr>
<tr>
<td>Stator self inductance</td>
</tr>
<tr>
<td>Rotor self inductance</td>
</tr>
<tr>
<td>Mutual inductance</td>
</tr>
<tr>
<td>No. of poles</td>
</tr>
<tr>
<td>Moment of inertia</td>
</tr>
</tbody>
</table>

Simulation Under Study

The two simulation models under study are:

1. Speed control of a direct field oriented induction motor drive using PID controller.
2. Speed control of a direct field oriented induction motor drive using a hybrid (PID + Fuzzy) controller

Performance comparison of induction motor using PID and a hybrid (PID plus Fuzzy) controller through waveforms

**Case I: At a load of 1.1 N-m (Rated Torque)**

From the Fig. 11 it is clear that when a load disturbance of 1.1 N-m is applied to an induction motor of 0.14 hp at 4.2 sec, the speed of PID controller drops to 876 rpm from 900 rpm which is reference speed. The performance parameters such as steady state error, overshoot and setting time are 0.002%, 0.4% and 0.2 sec respectively while in case of a hybrid (PID + Fuzzy) controller speed drops to 899 rpm from 900 rpm which is reference speed. The performance parameters such as steady state error, overshoot and setting time are 0%, 0.11% and 0.06 sec respectively.

![Fig. 11: Simulation results of the DFOIM using the hybrid controller and the PID under a load disturbance of 1.1 N-m](image)

**Case II: At 0 N-m (No load)**

From the Fig. 12 it is clear that when no load disturbance is applied, the PID controller shows negligible steady state error and overshoot of 0.11% while in case of hybrid (PID + Fuzzy) controller no steady state error and no overshoot is obtained.

![Fig. 12: Simulation results using the hybrid controller and the PID under no load](image)
Case III: At a load of 0.5 N-m (Under load)

Fig. 13: Simulation results of the DFOIM using the hybrid controller and the PID under a load disturbance of 0.5 N-m

From the Fig. 13 it is clear that when a load disturbance of 0.5 N-m is applied to an induction motor of 0.14 hp at 4.2 sec, the speed of PID controller drops to 890 rpm from 900 rpm which is reference speed. The performance parameters such as steady state error, overshoot and setting time are 0.003%, 1.1% and 0.05 sec respectively while in case of a hybrid (PID + Fuzzy) controller speed drops to 899.1 rpm from 900 rpm which is the reference speed. The performance parameters such as steady state error, overshoot and setting time are 0%, 0.1% and 0.04 sec respectively.

Case IV: At a load of 2 N-m (Overload)

Fig. 14: Simulation results of the DFOIM using the hybrid controller and the PID under a load disturbance of 2 N-m

From the Fig. 13 it is clear that when a load disturbance of 2 N-m is applied to an induction motor of 0.14 hp at 4.2 sec, the speed of PID controller drops to 860 rpm from 900 rpm which is reference speed. The performance parameters such as steady state error, overshoot and setting time are 0.002%, 4.5% and 0.05 sec respectively while in case of a hybrid (PID + Fuzzy) controller speed drops to 899.03 rpm from 900 rpm which is reference speed. The performance parameters such as steady state error, overshoot and setting time are 0%, 0.12% and 0.03 sec respectively.

Performance comparison of PID and hybrid (PID + fuzzy) controllers

Performance comparison of PID and Hybrid (PID + Fuzzy) controllers for speed control of Induction motors using DFO technique at a reference speed of 900 rpm and different loading conditions are given in the following table.

<table>
<thead>
<tr>
<th>Controllers</th>
<th>PID Controller</th>
<th>PID + Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Par.</td>
<td>Speed (rpm)</td>
<td>Steady State Error (%)</td>
</tr>
<tr>
<td>At a load of 1.1 N-m (Rated Torque)</td>
<td>876</td>
<td>0.002</td>
</tr>
<tr>
<td>At 0 N-m (no load)</td>
<td>899.9</td>
<td>0.001</td>
</tr>
<tr>
<td>At a load of 0.5 N-m (Under load)</td>
<td>890</td>
<td>0.003</td>
</tr>
<tr>
<td>At a load of 2 N-m (Over load)</td>
<td>860</td>
<td>0.002</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this paper, PID and a hybrid (PID + Fuzzy) Controller based speed control of a DFOIM drive is discussed for the analysis of various load conditions. The hybrid (PID + Fuzzy) controller has exhibited the combined advantages of a PID controller and a Fuzzy Logic Controller. It also has the capability of improving the stability, the transient response and load disturbance rejection of speed control of a DFOIM.

Moreover a performance comparison between PID & a hybrid (PID + Fuzzy) controller for the speed control of Induction motor is studied through simulation in MATLAB/Simulink environment. With results obtained from simulation and its comparison on the basis of steady state error, settling time and overshoot, it is clear that for the same operating conditions the hybrid (PID + Fuzzy) controller performs better than the PID controller. The steady state error is remarkably less in the case of the hybrid (PID plus fuzzy) controller. The fuzzy logic only with three membership functions are used for each input and output for low computational burden, which can achieve satisfactory results.

REFERENCES


