ANALYSIS OF V/f CONTROL OF INDUCTION MOTOR USING
CONVENTIONAL CONTROLLERS AND FUZZY LOGIC CONTROLLER

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Abstract – Induction motor speed control is necessary for many industrial applications, domestic applications and transportation. When we apply a load, the actual speed will vary from reference speed. By using different controllers the speed can be controlled. When by using conventional controllers the speed can be controlled satisfactorily but when by using artificial intelligence controller like fuzzy logic controller (FLC) it gives better performance than conventional controllers. So in this paper V/f speed control of induction motor using conventional controllers like PI, PID controllers and artificial intelligence controller fuzzy logic controller (FLC) are explained. All the simulations are done in MATLAB/SIMULINK environment

Keywords- Induction motor, V/f control, PI, PID controller, Fuzzy logic controller

I. INTRODUCTION

Induction motors are widely used in many applications due to its many advantages like high efficiency, low maintenance cost, robust construction etc. Speed control is required for many applications like industrial and domestic applications. When we apply a load the actual speed will differ from the reference speed. So for a particular application it is very important to maintain the actual speed and reference speed to the same value after load variation.

Many control techniques are available for speed control of induction motor. Out of these many techniques, scalar control and vector control are significant techniques. But scalar control is cheap and well implementable method, because of these advantages and simplicity, many applications in the industry operate with this control technique [1].

Here one of the scalar speed control method of V/f control using conventional controllers like PI, PID controllers and fuzzy logic controller are used and the comparison of their performance studies is done.

II. MODELING OF INDUCTION MOTOR

Induction motor is simulated in SIMULINK as it helps to achieve a transient behavior of electrical machine and drives. The model is valid under the two assumptions.

• Each stator phase of the motor has the same number of turns and uniform partial displacement
• Magnetic saturation is neglected.

Here the parameters of induction motor used are given in the appendix 1. The MATLAB/SIMULINK model of induction motor is developed using generalized mathematical equations given below.

\[
\frac{d}{dt} \psi_{qr} = \frac{\omega}{\omega_b} \left[ V_{qr} - \left( \frac{\omega}{\omega_b} \right) \psi_{dr} + \frac{R}{X_L} \left( \psi_{mq} - \psi_{qr} \right) \right]
\]

\[
\frac{d}{dt} \psi_{dr} = \frac{\omega}{\omega_b} \left[ V_{dr} - \left( \frac{\omega}{\omega_b} \right) \psi_{qr} + \frac{R}{X_L} \left( \psi_{md} - \psi_{dr} \right) \right]
\]

\[
\frac{d}{dt} \psi_{dr} = \frac{\omega}{\omega_b} \left[ V_{dr} - \left( \frac{\omega}{\omega_b} \right) \psi_{dr} + \frac{R}{X_L} \left( \psi_{md} - \psi_{dr} \right) \right]
\]

\[
\frac{d}{dt} \psi_{dr} = \frac{\omega}{\omega_b} \left[ V_{dr} - \left( \frac{\omega}{\omega_b} \right) \psi_{qr} + \frac{R}{X_L} \left( \psi_{mq} - \psi_{qr} \right) \right]
\]
q axis and d axis stator currents $i_{qs}$, $i_{ds}$, $i_{qr}$, $i_{dr}$:

$$i_{qs} = \frac{1}{X_{ls}} (\psi_{qs} - \psi_{mq})$$

(5)

$$i_{ds} = \frac{1}{X_{ls}} (\psi_{ds} - \psi_{md})$$

(6)

$$i_{qr} = \frac{1}{X_{lr}} (\psi_{qr} - \psi_{mq})$$

(7)

$$i_{dr} = \frac{1}{X_{lr}} (\psi_{dr} - \psi_{md})$$

(8)

Based on the above equations, the torque and rotor speed are:

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{1}{\omega_b} (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})$$

(9)

$$\omega_r = \int \frac{P}{2J} (T_e - T_f)$$

(10)

Figure 1: MATLAB/SIMULINK model of Induction motor drive

By using the generalized equations, the MATLAB/SIMULINK model developed is given in figure 1. The rated power of induction motor is 5HP and reference speed is 1500rpm. From figure 2, at no load, both the reference speed and actual speed are same before applying the load. The rated torque of 23 Nm is applied at a step time of 2.5s. Then the speed decreases to the speed of 1478 rpm as shown in the simulation result. From figure 3, at starting, the torque is very high and reaches a value of 325 Nm, and then reaches to 0 at no load condition, and then settles to the rated torque of 23 Nm at a step time of 2.5s.

Figure 2: Speed vs time graph.
III. V/f CONTROL OF INDUCTION MOTOR

The figure 4 shows the schematic block diagram of closed loop of V/f control. The actual speed of the rotor is compared with its commanded value \( \omega_r \), and the error is processed through a controller, and a limiter to obtain the slip speed command \( \omega_{sl} \). The limiter ensures that the slip speed command is within the maximum allowable slip speed of the induction motor [2-3]. The slip speed command is added to the electrical rotor speed to obtain the stator frequency command.

IV. V/f CONTROL OF INDUCTION MOTOR USING DIFFERENT CONTROLLERS

The complete MATLAB model for the simulation is given in the figure 5. The controller portion changes with the different controllers. The inverter here used for modulation is Sine Pulse Width Modulator (SPWM). The frequency signal from the controller will change the width of voltage pulses of the SPWM to keep the V/f ratio constant. The output equations of the SPWM are:

\[
V_a = \frac{2}{3} \sqrt{2} \left( 2u(1) - u(2) - u(3) \right)
\]

\[
V_b = \frac{2}{3} \sqrt{2} \left( 2u(2) - u(3) - u(1) \right)
\]

\[
V_c = \frac{2}{3} \sqrt{2} \left( 2u(3) - u(2) - u(1) \right)
\]

The simulation graphs for different controllers are also given below.
A. PI CONTROLLER

PI controller will eliminate the forced oscillations and steady state error of P controller. However introducing the integral mode will have adverse effect on the stability of the system and speed of response [4]. So the PI controller will not increase the speed of response and also the PI controller cannot predict what will happen with the error in near future.

PI controllers are usually used in the place when speed of response is not an issue. Also this controller can be used when there is a large transport delays in the system, and when there is only one energy storage process is present. PI controller can effectively work when there is a presence of a noise or large disturbance during the operation of a process.

The PI speed controller gains are selected by trial and error method by observing their effects on the response of the drive. Figure 6 shows the speed response of IM drive at reference speed of 1500 rpm and load torque of 23 Nm is applied at 2.5 s. Here the rise time is 0.0197 s and the settling time is 1.5 s. The induction motor drive speed decreased during loaded condition, but due to the effect of PI controller the speed catches to reference speed within a time.

Figure 7 shows the speed response of induction motor drive at reference speed of 1200 rpm and load torque of 23 Nm is applied at 2.5 s. Here the rise time is 0.022 s, and settling time is 1.0 s. Then due to the effect of PI controller, speed catches to the reference speed within a time of 1.3 s after applying the load.

![Figure 6: Speed vs time graph of PI controller at a reference speed of 1500 rpm](image)

![Figure 7: Speed vs time graph of PI controller at a reference speed of 1200 rpm](image)

B. PID CONTROLLER

By using their 3 basic behavior types or modes: P- proportional, I- integrative, D- derivative PID controller will control the speed of the IM drive. The proportional and integrative control mode is used as single control method but the derivative mode is rarely used on its own in control system.

PID controller has all the necessary dynamics such as suitable action inside control error area to eliminate oscillations (P mode), increase in control signal to lead error towards zero (I mode) and fast reaction on change in control input (D mode). Derivative mode improves stability of the system and enables increase in gain K and decrease in integral time constant Ti, which increases speed of the controller response [5]. PID controller is used when dealing with processes with more than one energy storage when their dynamic is not similar to the dynamics of an integrator.
If the PID controllers are tuned properly they can provide robust and reliable control. This very feature has made PID controller exceedingly popular in industrial applications. PID controller is also used in the control of mobile objects (course and trajectory following included) when stability and precise reference following are required.

The PID speed controller gains are selected by trial and error method by observing their effects on the response of the drive. Figure 8.3 shows the speed response of IM drive at reference speed of 1500 rpm and load torque of 23 Nm is applied at 2.5s. From figure 8 it can be seen that rise time is 0.1027 s and settling time is 0.25 s. Here the speed catches with reference speed at a time of 0.25s after applying load torque. Here due to the effect of integral mode and derivative mode the speed of response increases and so that actual speed will catch the reference speed more quickly.

Figure 9 shows the speed response of IM drive at reference speed of 1200 rpm. Here the rise time is 0.0943 s and settling time is 0.2 s. Here the speed catches to the reference speed at a time of 0.2s. At 2.5 s rated torque of 23 Nm is applied and due to the effect of PID controller the speed catches the reference speed without much delay as shown in figure 9.

C. FUZZY LOGIC CONTROLLER

Fuzzy logic control is a control algorithm based on a linguistic control strategy which is derived from the expert knowledge into automatic control strategy. Based on the qualitative knowledge about the system being controlled, the operation of FLC is performed. FLC use simple mathematical calculation to simulate expert knowledge while other control systems use difficult mathematical calculation to simulate the expert knowledge [6]. It gives good performance even though it does not need any difficult mathematical calculation. Due to these reasons, now a days FLC is the best available answer for a broad class of challenging control problems.
Figure 10: Simulation model of interior part of the Fuzzy Logic Controller

The complete MATLAB /SIMULINK model is shown in figure 5. Here instead of PI or PID controller we can use Fuzzy logic controller as well. The figure 10 shows the simulation model of interior portion of the controller. The speed error and change in speed error is then given as input to the Fuzzy Logic Controller and the output which is the control signal frequency is then send to the SPWM inverter, such that it changes the voltage so that V/f ratio kept constant. As a result the output speed (actual speed) of motor will be same as the reference speed. The rule table used for fuzzy control is given in table 1.

<table>
<thead>
<tr>
<th>de/dt e</th>
<th>N2</th>
<th>N1</th>
<th>Z</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>N4</td>
<td>N4</td>
<td>N4</td>
<td>N3</td>
<td>Z</td>
</tr>
<tr>
<td>N1</td>
<td>Z</td>
<td>N2</td>
<td>N1</td>
<td>Z</td>
<td>P3</td>
</tr>
<tr>
<td>Z</td>
<td>N4</td>
<td>N1</td>
<td>N1</td>
<td>Z</td>
<td>P1</td>
</tr>
<tr>
<td>P1</td>
<td>N3</td>
<td>Z</td>
<td>P1</td>
<td>P2</td>
<td>P4</td>
</tr>
<tr>
<td>P2</td>
<td>Z</td>
<td>P3</td>
<td>P4</td>
<td>P4</td>
<td>P4</td>
</tr>
</tbody>
</table>

Figure 11 shows the speed response of induction motor drive at reference speed of 1500 rpm and load torque of 23 Nm is applied at 2.5 s. Here the rise time is 0.0365 s and the settling time is 0.064 s. The IM drive speed does not decrease when applying load due to the effect of fuzzy logic controller.

Figure 12 shows the speed response of induction motor drive at reference speed of 1200 rpm and load torque of 23 Nm is applied at 2.5 s. There is a rise time at the starting before the settling time. The rise time is 0.0298 s. Here the settling time is 0.051 s, and then due to the effect of FL controller, when load applies at a time of 2.5 s, the actual speed does not fall down below the reference speed.

Figure 11: Speed vs time graph of fuzzy logic controller at a reference speed of 1500 rpm
V. COMPARATIVE ANALYSIS OF CONVENTIONAL CONTROLLERS AND FUZZY LOGIC CONTROLLER

It is clear that when a controller is not used the actual speed and reference speed differs. But by using a controller the performance of motor changes.

A. COMPARATIVE ANALYSIS

Table 2: Comparative analysis of different controllers

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Controller</th>
<th>Rise time (sec)</th>
<th>Settling time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>PI</td>
<td>0.022</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0943</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>FLC</td>
<td>0.0298</td>
<td>0.051</td>
</tr>
<tr>
<td>1500</td>
<td>PI</td>
<td>0.0197</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.1027</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>FLC</td>
<td>0.0365</td>
<td>0.064</td>
</tr>
</tbody>
</table>

By analyzing the results obtained for conventional (PI, PID) controllers and Fuzzy logic controller, it is observed that the settling time is smaller for FLC and rise time is smaller for conventional controllers. However when the speed changes from reference speed that is either speed increased or decreased from the reference speed the FLC shows better response than the conventional controllers. FLC catches the new speed very faster than the conventional controllers with a less settling time. These results are evident from the table 2.

B. COMPARATIVE ANALYSIS- SPEED RANGE

The figure 13 shows the maximum and minimum speed range of different controllers. Here the load torque applied is 23 Nm at a time of 2.5 s

By analyzing the results obtained for conventional (PI, PID) controllers and Fuzzy logic controller, it is observed that the settling time is smaller for FLC and rise time is smaller for conventional controllers. However when the speed changes from reference speed that is either speed increased or decreased from the reference speed the FLC shows better response than the conventional controllers. FLC catches the new speed very faster than the conventional controllers with a less settling time. These results are evident from the table 2.
It is evident from the figure 13 that the maximum and minimum speed range that can be controlled by conventional controllers is less than that can be controlled by using a Fuzzy logic controller. Also there is some distortion in the wave form obtained using conventional controller, but by using Fuzzy logic controller the graph obtained is a smooth one.

Since induction motor is a nonlinear system, conventional controllers will not provide accurate control. But for linear system, conventional controllers provide better results. FLC is a nonlinear controller which is designed on a rule base which is user defined. So FLC can provide better control of speed with minimum error since induction motor is also a nonlinear system.

VI. CONCLUSIONS

The closed loop V/f control of IM drive is simulated in MATLAB/SIMULINK using PI, PID and fuzzy logic controllers. The major conclusions obtained are as follows:

The both conventional controllers and fuzzy logic controller will catch the reference speed at loaded and no load condition, but the time taken by fuzzy logic controller to catch the reference speed and settling time is very much less than the conventional controller. The rise time taken by the conventional controller is less than the fuzzy logic controller; this is the disadvantage of fuzzy logic controller when compared with the conventional controller. By using fuzzy logic controller the speed range that can be controlled is more than conventional controller.

From the results it is seen that fuzzy logic controller is better than the conventional controllers.

APPENDIX A

The following parameters of induction motor are selected for the simulation studies:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP</td>
<td>5 HP</td>
</tr>
<tr>
<td>Rated stator voltage</td>
<td>220 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated current</td>
<td>13.54 A</td>
</tr>
<tr>
<td>No of poles</td>
<td>4</td>
</tr>
<tr>
<td>Speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Moment of inertia, J</td>
<td>0.1111 kg m²</td>
</tr>
</tbody>
</table>
Rotor resistance, $R_r$       0.39 $\Omega$
Stator resistance, $R_s$       0.49 $\Omega$
Mutual inductance, $L_m$       2e-3 H
Stator inductance, $L_s$       0.71e-3 H
Rotor inductance, $L_r$       0.5e-3 H

REFERENCES