Quick-Response Fuzzy-Controlled Induction Motor Drive

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ABSTRACT

High performance motor drives require high accuracy, fast response, wide range of control, robustness and immunity from the effect of parameter variations. Three phase motors have a complex and highly nonlinear mathematical model associated with interactive parameters. This makes designing a conventional controller for such a system is a hard task. Researchers are paying more attention to fuzzy logic controllers (FLCs) since they can be employed to control complex or nonlinear systems even without knowing their mathematical model. The main task of this paper is to design and implement an FLC for indirect field orientated control of a three phase induction motor drive. The proposed controller is a proportional-derivative (PD) FLC. It uses the speed and its derivative as input and the electromagnetic torque as output. The input and output are coupled with simple linguistic if-then rules. The spread of each input and output is adjusted using a gain block to achieve the best performance in a trial-and-error process. Also, an incremental counter is attached to the output of the controller to yield the desired electromagnetic torque. The design was implemented and tested using MATLAB/SIMULINK. Finally, the simulation results and figures were presented.

Keywords: Fuzzy controller, rule base, indirect field oriented control, induction motor drive, speed control.

1 Introduction

Vector control techniques have been used widely to control three phase induction motor drives. The motor torque and flux are controlled by acting on the space vectors of the stator current [1]. Indirect field oriented control is one of the common used vector control techniques. It has the advantage of using only current and speed sensors. Its principle is based on resembling a separately excited DC motor [2]. Classical proportional-integral (PI) controllers are employed in the control technique [3 , 4]. However, designing a PI controller for the induction motor drive is a difficult task since the induction motor model is highly nonlinear, inaccurate and having interactive parameters [5 , 6]. Fuzzy logic applications to induction motor include control, performance enhancement, fault detection and motor diagnoses [7, 8]. FLCs may be used in conjunction with other classical controllers to control induction motor drives. The FLC, in this case, is used to adapt classical PI or PID controller parameters according to the variations in the controlled system [9]. Also, it can be used in a standalone form to replace classical controllers [10]. The standalone constant-structure FLC has the advantage for being simple to design, build and tune.

2 Indirect Field Oriented Control

The principle of indirect field oriented control is based on resembling a separately excited DC machine, where the field at some point, is kept constant while the armature current is controlled in order to control the motor speed [2]. Park's transform is widely used in the analysis of induction motors. It refers stator current and voltage vectors to a fixed frame to the rotor, which in turn has a direct and quadratic (d-q) components [11]. Generally, the generated electromagnetic field of a three-phase induction motor in the d-q fictitious frame is given by:

$$T_{em} = \frac{2}{3} p_p \frac{L_m}{L_r} (i_{sq}\lambda_{rd} - i_{sd}\lambda_{rq}) \quad (1)$$

where p_p is the number of pole pairs; L_m is the mutual inductance; L_r is the rotor inductance; i_{sd}, i_{sq} are the d- and q-axis stator current components; $\lambda_{rd}, \lambda_{rq}$ are the d- and q-axis rotor flux linkage components.

In order to make the torque equation similar to that one of the separately excited DC machine, λ_{rq} is set to zero so that $\lambda_{rd} = \lambda_r$. This only can be done by adjusting the angle between the rotor flux linkage and stator current vector to keep λ_r aligned to the d-axis by increasing or decreasing i_{sq}component as shown in Figure 1.

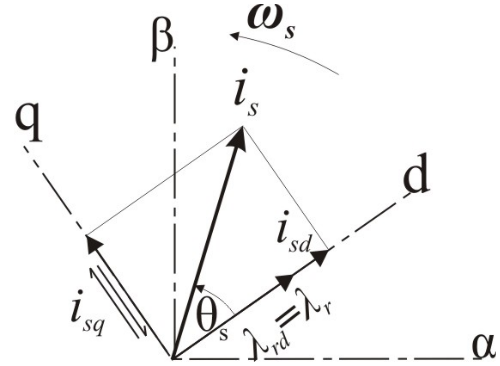

Figure 1: Principle of indirect field oriented control

Both the rotor flux and the synchronous angle (θ_s) are estimated from the measured stator currents and rotor's mechanical speed. The measured mechanical speed and the estimated slip angle are integrated in order to calculate the synchronous angle (θ_s).

$$\theta_s = \int \left(p_p\omega_m + \frac{L_m}{\tau_r} \frac{i_{sq}}{\lambda_{rd}} \right) dt \quad (2)$$

where ω_m is the mechanical angular speed and $\tau_r = L_r/R_r$ is the rotor time constant.

Meanwhile the rotor flux component (λ_{rd}) is obtained by solving the following differential equation

$$\frac{\lambda_{rd}}{\tau_r} + \frac{d\lambda_{rd}}{dt} = \frac{L_m}{\tau_r}\ i_{sd} \tag{3}$$

where $\lambda_{rd} = \lambda_r$ and $\lambda_{rq} = 0$.

The desired (i_{sq}^*) component is calculated from equation (1)

$$i_{sq}^* = \frac{3}{2}\frac{L_r}{L_m}\frac{T_{em}^*}{\lambda_r} \tag{4}$$

where T_{em}^* is desired electromagnetic torque.

Meanwhile, the desired direct–axis stator current (i_{sd}^*) is obtained from equation (3) at steady-state, so that $\frac{d\lambda_{rd}}{dt} = 0$.

$$i_{sd}^* = \frac{\lambda_r}{L_m} \tag{5}$$

The inverse of Park's transform is applied on (i_{sd}^* and i_{sq}^*) compnents to obtain stator reference current ($i_{s_{abc}}^*$). The measured stator currents ($i_{s_{abc}}$) are compared with the reference ones ($i_{s_{abc}}^*$) in order to generate the required ON/OFF signals for the DC/AC inverter.

3 FLC Structure

The fuzzy logic controller is a microcontroller embedded into the system and designed to work with fuzzy mathematics. The block diagram of a typical FLC is shown in **Figure** 2. The expert or designer shall have the access to set many parameters including number of inputs and outputs, type and number membership functions, spread, fuzzy rules, aggregation, implication and defuzzification methods.

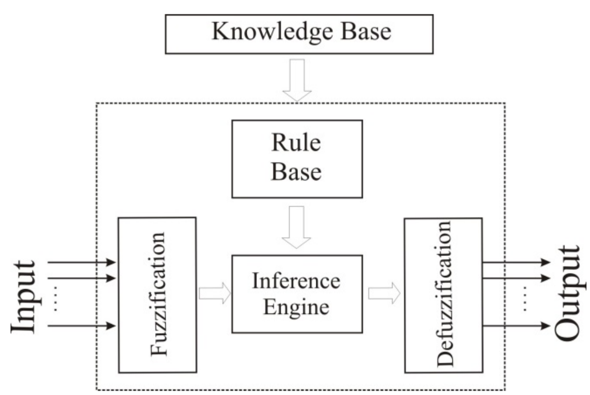

Figure 2: FLC block diagram

In general, an FLC consists of the following components:

3.1 The Fuzzification Layer

This layer transforms the inputs, which are in single values (crisp) form, to the correspondent defined fuzzy membership functions. The fuzzy controller may have more than one input.

3.2 Inference Engine

The inference engine performs with the fuzzy calculations. First, it implicates the fuzzy inputs based on the provided rules. Then, it collects (aggregates) the implicated membership functions of the output.

3.3 Rule Base

The rule base is a set of rules in the form of if-then format that links the membership functions of input and output. The number of rules must cover all the defined membership functions of inputs and outputs. Setting the rules use the human knowledge and expertise in easy linguistic terms.

3.4 The Defuzzification Layer

The aggregated fuzzy output from the inference engine is unusable unless it is turned back to a single value (crisp) form. This process is called defuzzification. The aggregated fuzzy shape is weighed and normalized to obtain one crisp value at a time for each output.

4 Simulation

The design and simulation work of the induction motor drive were done by using MATLAB/SIMULNK. The general block diagram of the proposed system is presented in Figure 3. The motor was fed by a DC power source via an inverter while the speed and stator current were measured in order to be used in the control process. The design of the system went through two stages.

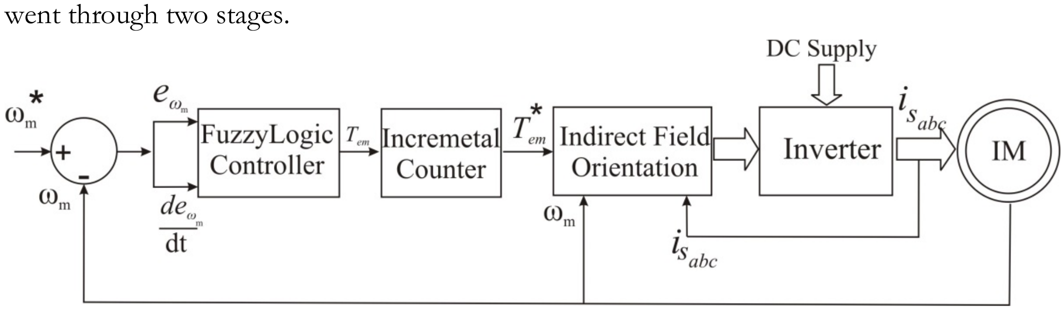

Figure 3: Block diagram of the proposed induction motor drive

4.1 Indirect Field Orientation Unit

The modelling equations in section 2 were used to build the indirect field oriented control block as shown in Figure 4. Equation 2 was used to estimate the current angle using the mechanical speed, the estimated rotor flux and the direct component of stator currents. The rotor flux vector (λ_r) was estimated by solving equation 3 while the desired quadratic current component was calculated using the incremental counter output (T_{em}^*) and rotor flux. Park's transform was used to resolve the measured currents into the d-q farm, and its inverse for getting the desired stator currents ($i_{s_{abc}}^*$) from their d-q counterparts. The measured and the desired currents were compared in a hysteresis band controller in order to produce the necessary ON/OFF signals for power switching device.

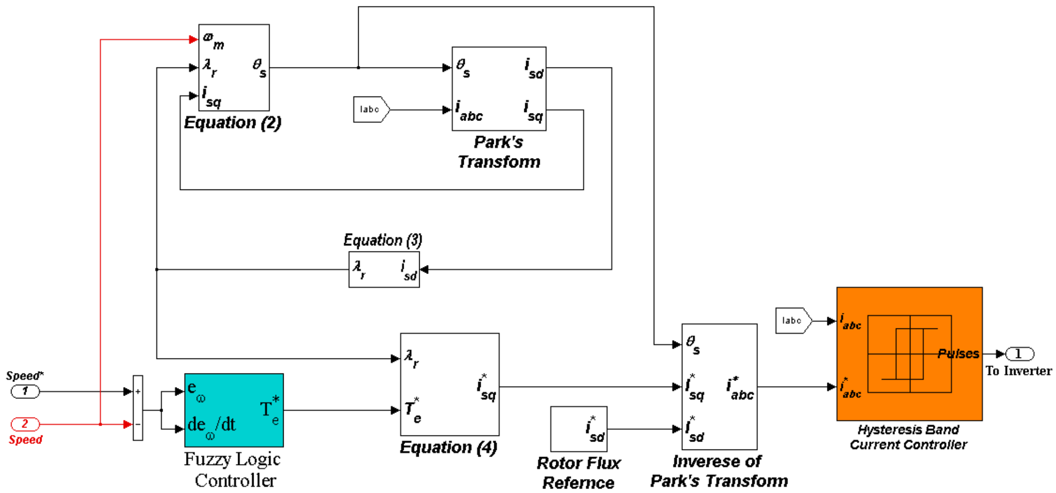

Figure 4: Control unit

A medium size of a 30hp three phase squirrel-cage induction motor was used in simulation with its rated parameters defined in Table 1 [12].

Table 1: Induction motor parameters

Parameter	Symbol	Value
Nominal supply voltage	v_s	400V
Nominal stator current	i_s	39.1A
Nominal frequency	f	60Hz
Pole pairs	p_p	3
Nominal rotor speed	n_m	1146rpm
Stator resistance	R_s	0.294Ω
Stator leakage inductance	L_{ls}	1.4mH
Stator resistance	R_r	0.156Ω
Rotor leakage inductance	L_{lr}	0.74mH
Mutual inductance	L_m	41mH

4.2 Fuzzy Control Unit

The proposed PDFLC was designed using MATLAB fuzzy toolbox. Both speed error and its rate of change were used as input and the electromagnetic torque as an output where five triangular membership functions were assigned to each one of them as shown in Figure 5.

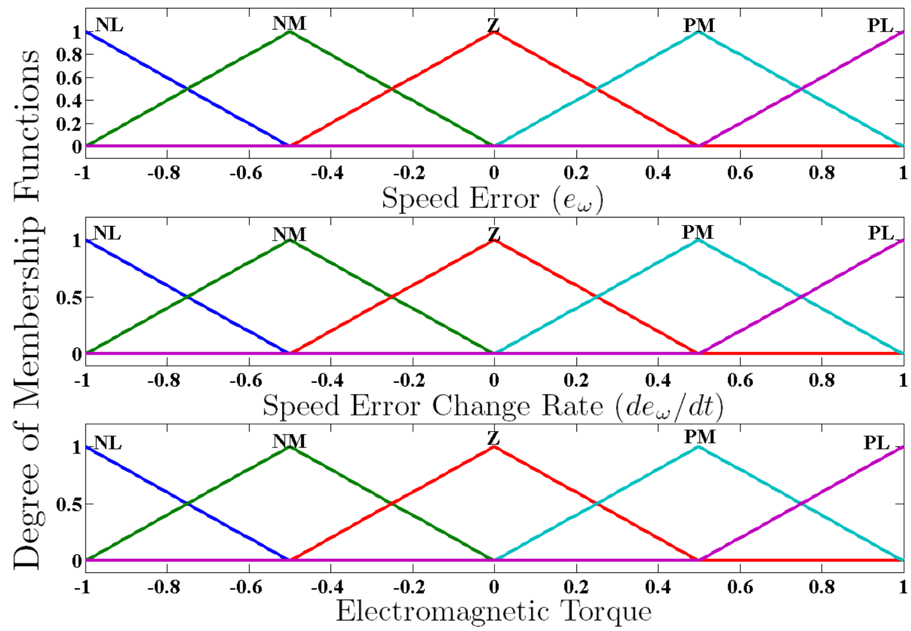

Figure 5: Controller membership functions

The membership functions were linearly distributed and their spreads were adjusted using gain blocks on input and output. The rule base was established based on the expertise knowledge in 25 rules as Table 2 shows.

Table 2: PD Fuzzy logic controller rules

de_{ω_m}/dt \ e_{ω_m}	**NL**	**NM**	**Z**	**PM**	**PL**
NL	NL	NL	NM	NM	Z
NM	NL	NM	NM	Z	PM
Z	NM	NM	Z	PM	PM
PM	NM	Z	PM	PM	PL
PL	Z	PM	PM	PL	PL

where **NL** is negative large, **NM** is negative medium, **Z** is zero, **PM** is positive medium, and **PL** positive large.

Also, an incremental counter with delayed positive unity feedback was used on the controller output to generate the desired electromagnetic torque (T_{em}^{*}) as shown in Figure 6. The counter holds its output constant until the next cycle occurs. The new output of the counter is combined of the summation of the delayed T_{em}^{*} and the real-time FLC output (T_{em}). The controller output has the effect of gradual increasing or decreasing T_{em}^{*}. The incremental counter has two functions. First, it stabilizes the drive operation even when the output of the controller is zero. Second, it has a limiter to keep the motor current within the safe limits.

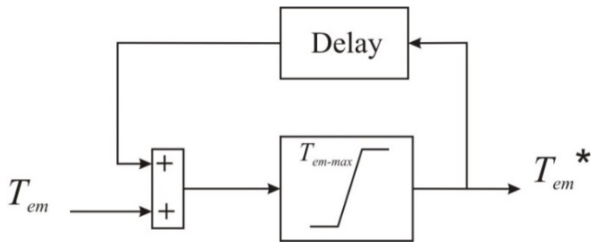

Figure 6: An incremental counter with delayed feedback

5 Results

After the controller gains were tuned to obtain the best results, all simulation data were captured and kept in order to be analysed. The drive was first started to run at 764 rpm and then a speed step change was applied at 0.4 sec to reach 1146 rpm without applying load. At 0.8 sec the load is applied as shown in Figure 7.

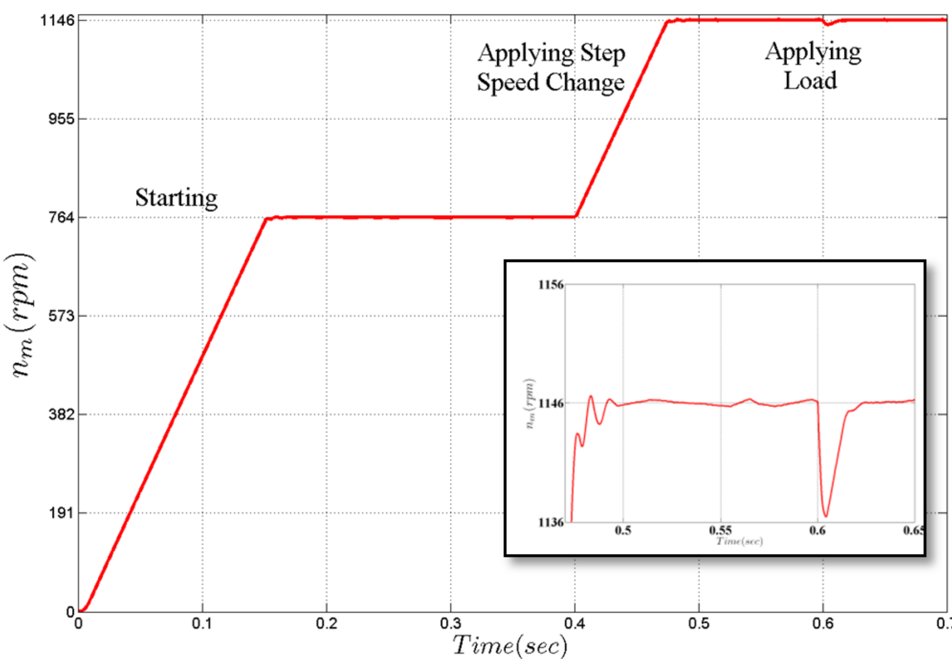

Figure 7: Induction motor drive speed response curve

The peak overshoot for the applied step speed change was almost neglected. However, speed dropped momentarily by 10rpm when load was applied which represents only 0.87 % of the motor speed. The speed response was fast and constant until it became very close to the setting speed.

Finally, the stator motor currents were plotted Figure 8. The plot clearly shows the change of current angles as a variation of speed or torque were applied. This change in the angle was done to keep the rotor flux aligned to direct axis when drifting occurred.

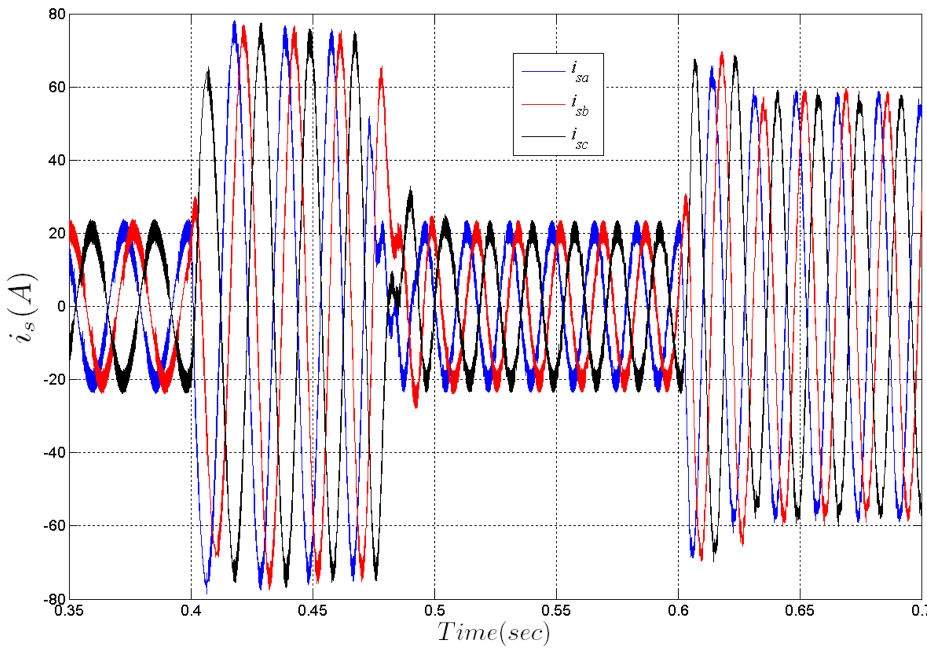

Figure 8: Motor currents

6 Conclusions

This paper investigated the design and implementation of a PD fuzzy logic controller for indirect field orientated control of a three-phase induction motor drive. The speed error and its derivative were used as controller input while the electromagnetic torque as controller output. Each input and output had five triangular membership functions. The cases of input and output were joined together with 25 if-then fuzzy rules. Only the spread of fuzzy sets of each individual input and output was adjusted to obtain the best performance. In addition, an incremental counter attached to the controller output was used to stabilize the system. Measured stator currents and rotor speed were used to decouple the rotor flux and the current angle in order to be used in conjunction with the incremental counter output to generate the required stator currents for field orientation. The proposed PD fuzzy logic controller achieved fast response, small peak overshoot, wide range of speed control and fast recovery time when variations in speed and load were applied.

References

[1] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of PWM inverter-fed AC motors - a survey," *IEEE Trans. Ind. Electron.,* vol. 51, no. 4, pp. 744-757, Aug. 2004.

[2] F. Blaschke, "The principle of field orientation as applied to the new transvector closed-loop control system for rotating-field machines," *Siemens Rev.,* vol. 39, no. 5, pp. 217-220, 1972.

[3] Ahallianath K G R and W. Beevi M, "Indirect field oriented control of induction motor using predictive current controller," *2015 Int. Conf. on Control Commun. & Computing.*, India, pp. 248-253, ICCC. 2015.

[4] B. K. Nishad and R. Sharma, "Induction motor control using modified indirect field oriented control," *8th IEEE India Int. Conf. on Power Electron.*, JAIPUR, India, pp. 1-5, IICPE. 2018.

[5] S. Pati, M. Patnaik, and A. Panda, "Comparative performance analysis of fuzzy PI, PD and PID controllers used in a scalar controlled induction motor drive, "*Proc. Int. Conf. Circuits, Power Comput. Technol.*, pp. 910-915, ICCPCT. Mar. 2014

[6] A. L. Murari *et al.*, "A proposal of project of PI controller gains used on the control of doubly-fed induction generators," *IEEE Latin Amer. Trans.*, vol. 15, no. 2, pp. 173-180, Feb. 2017.

[7] K. Hsu *et al.*, "Enhanced fuzzy sliding mode control to motion controller of linear induction motor drives," *2014 IEEE Int. Conf. on Syst. Sci. and Eng.* , Shanghai, pp. 268-273, *ICSSE.* 2014.

[8] D. A. Surwase, A. S. Jalit and M. D. Chavan, "Fault detection and protection of induction motor using fuzzy logic," *2017 Int. Conf. on Innovations in Elect., Electron., Instrum. and Media Technol*, Coimbatore, India, pp. 66-70, *ICEEIMT.* 2017.

[9] A. Kumar R and F. Daya J L, "A novel self-tuning fuzzy based PID controller for speed control of induction motor drive," *2013 In.l Conf. Control Commun. and Comput.,* India, pp. 62-67, ICCC. 2013 .

[10] M. Pandey and A. Brave, "An intelligent fuzzy logic controlled based induction motor drive," *Int. J. Sci. Res.*, vol. 4, no. 6, pp. 1092-1096, Jun. 2015.

[11] R.H. Park, "Two-reaction theory of synchronous machines generalized method of analysis-part I," *Trans. AIEE*, vol. 48, no. 3, pp. 716–730, 1929.

[12] A. Trzynadlowski, *Control of Induction Motors*. San Diego, CA: Academic Press, 2001.