A FUZZY-BASED SPEED CONTROLLER FOR IMPROVEMENT OF INDUCTION MOTOR'S DRIVE PERFORMANCE

H. ASGHARPOUR-ALAMDARI, Y. ALINEJAD-BEROMI AND H. YAGHOBI

Abstract. Induction motors (IMs) are widely used in many industrial applications due to their robustness, low cost, simplicity and relative good efficiency. One of the major considerations for IMs is their speed control. PI (proportional-integrator) controllers are usually used as speed controller. Adjusting the gain of PI controller is time-consuming which needs thorough considerations. Hence, fuzzy controllers are proposed to overcome such problems. In this paper, firstly drive of a three-phase induction motor is designed based on PI controller and then fuzzy logic controller is implemented. This paper presents a novel speed control technique based on fuzzy logic with two inputs and one output for drive of an IM. The inputs are speed error and derivation of speed error and the output is speed. Finally comparison is done between the PI and fuzzy controllers which shows superiority of the fuzzy controller over PI controller.

1. Introduction

Electrical motors are one of the most applicable elements in electricity industry. Induction motors are the most prominent electrical motors. Speed control is an important issue in which it is always tried to reach to the desirable response in minimum time. Difficult methods were used for speed control in past such as changing pole numbers, voltage control and etc. Some of these methods are now out of use. By passing time and developing power-electronics, new methods are proposed such as vector control in which voltage and frequency are changed simultaneously in order to control the speed of motor like a DC motor. Despite all the efforts, accuracy of these methods is also low and there should be controllers in order to speed up the process. In conventional systems, PI controllers are usually used. This kind of controller is a combination of proportional and integrator controllers in which the aim is to reach to the desired response with minimum time and maximum accuracy. Adjusting PI controller is a difficult and time-consuming process low and in some cases final response is not achieved. Therefore, researchers thought of a new controller in order to overcome such problems. For this purpose, PI controllers are replaced by fuzzy logic controllers. One of the good features of fuzzy controllers over PI controllers in induction motor is that they reach quicker to the final response and steady-state condition.

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There are great deals of researches pertaining to speed control of IMs by using fuzzy controllers. In [14], an intelligent speed control is presented for obtaining maximum torque and efficiency based on fuzzy logic. A review study about optimization of induction motor efficiency by using different methods such as neural network, fuzzy logic and etc is presented [15]. Speed control of induction motor using fuzzy logic and PWM technique is discussed [7]. Closed-loop control with voltage inverter system is considered using fuzzy logic controller for induction motor and it is compared with PI controller [18]. Design of fuzzy controller for drive of induction motor using current source inverter is investigated in [10]. In [17], drive of an induction motor is simulated using ANFIS instead of conventional PI controller. This new method has better characteristics and less error or overshoot. Other surveys are devoted to similar issues with various controllers mainly fuzzy controllers [3, 4, 5, 12, 20, 21]. The controller design of induction motor by PI and fuzzy controllers are discussed in order to increase the efficiency, reduction of core loss and reaching to the desired speed [2, 6, 9, 13]. In [8, 11, 16, 19], efficiency of the induction motor is optimized using Neuro-Fuzzy, ANFIS and Neural network.

In this paper, Mamdani model with two inputs and one output is designed and investigated for induction motor. Main characteristic of this method is that the value and importance of the inputs is different. Employing two different inputs leads to faster and more accurate response.

The rest of the paper is organized as follows: section 2 presents model of induction motor and state-space equations. In section 3, fuzzy logic and its application in induction motor is discussed. Simulation is performed in section 4 where PI and fuzzy controllers are compared. Finally, paper is concluded in section 5.

2. **Model of Induction Motor**

The model of induction motor is well recognized in the literatures. Therefore, the main and important equations are presented. (1) to (4) are required equation for performing simulation [3]. Equivalent circuit of the induction motor is also shown in Figure 1.

$$
\begin{aligned}
v_{qs} &= R_s\, i_{qs} + \frac{d}{dt}\,\Phi_{qs} + \omega\Phi_{ds} \\
v_{ds} &= R_s\, i_{ds} + \frac{d}{dt}\,\Phi_{ds} - \omega\Phi_{qs} \\
v_{qr} &= R_r\, i_{qr} + \frac{d}{dt}\,\Phi_{qr} + (\omega - \omega_r)\,\Phi_{dr} \\
v_{dr} &= R_r\, i_{dr} + \frac{d}{dt}\,\Phi_{dr} - (\omega - \omega_r)\,\Phi_{qr} \\
T_e &= \frac{3}{2}\,P\,(\Phi_{ds} i_{qs} - \Phi_{qs} i_{ds})
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\Phi_{qs} &= L_s i_{qs} + L_m i_{qr}' \\
\Phi_{ds} &= L_s i_{ds} + L_m i_{dr}' \\
\Phi_{qr}' &= L_r' i_{qs}' + L_m i_{qs}' \\
\Phi_{dr}' &= L_r' i_{dr}' + L_m i_{ds}
\end{aligned}
\tag{2}
$$

$$L_s = L_{ls} + L_m$$

$$L_r' = L_{lr}' + L_m \tag{3}$$

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m)$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{4}$$

where parameters of the induction motor are defined as follow:

R_s and R_r' are stator and rotor resistance, respectively. L_{ls} and L_{lr}' are stator and rotor leakage inductance, respectively. L_m is magnetizing inductance. L_s and L_r' total inductances of stator and rotor. v_{qs} and i_{qs} are stator voltage and current of q axis. v_{qr}' and i_{qr}' are rotor voltage and current of q axis. v_{ds} and i_{ds} are stator voltage and current of d axis and v_{dr}' and i_{dr}' are rotor voltage and current of d axis. ϕ_{qs} and ϕ_{ds} stator q and d axis fluxes and ϕ_{qr}' and ϕ_{dr}' are rotor q and d axis fluxes. ω_m is rotor angular velocity. θ_m is angular position of the rotor. P is pole pairs number. ω_r is electrical angular velocity (ω_m.p). θ_r is electrical rotor angular position (θ_m.p). T_e is electromagnetic torque. T_m is Mechanical torque of shaft. J is joined rotor and load inertia coefficient. H is joined rotor and load inertia constant. F is joined rotor and load viscous friction coefficient [9].

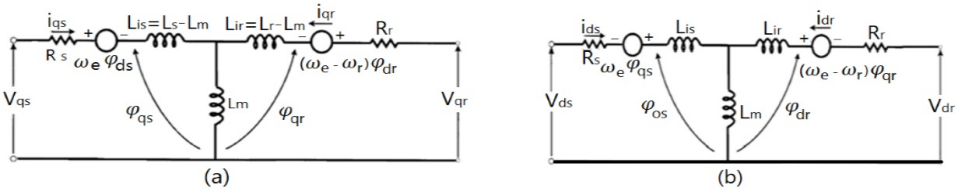
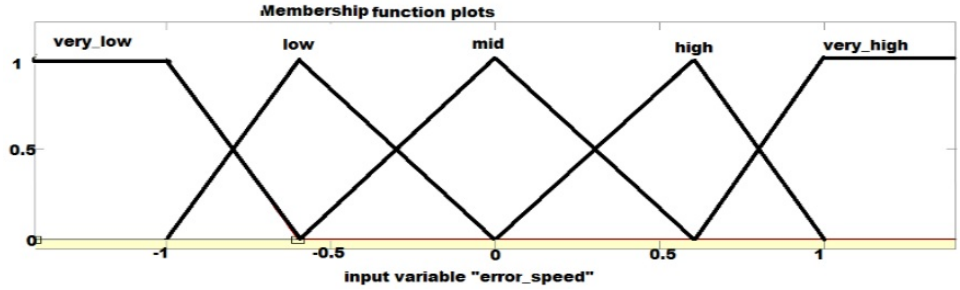


FIGURE 1. Equivalent Circuit of Induction Motor for d, q Axis System

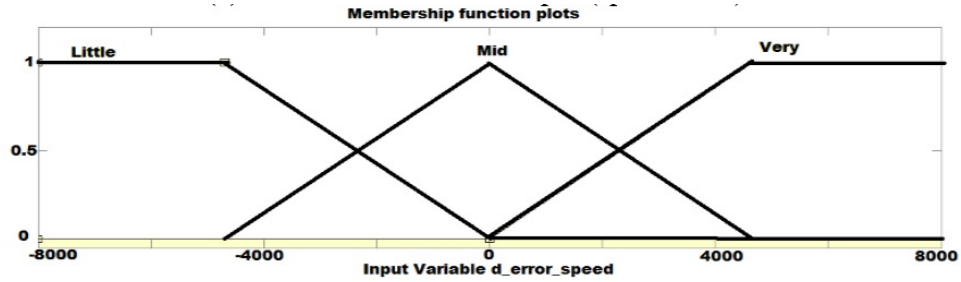
3. **Definition of Fuzzy Logic**

Fuzzy logic is an approach for easy and flexible modeling of complex systems that their modeling is difficult and in some cases impossible by mathematics or classic modeling methods. Structure of fuzzy logic is based on the theory of fuzzy sets. This theory is a generalized state of theory of classic sets in mathematics. In classic theory, one element has two states. It is the member of the set or it is not. In fact, membership of the elements is based on a zero/one binary pattern. But, theory of fuzzy sets expands this concept and presents weighted membership. One of the interesting aspects of fuzzy logic is its interpretation about intelligent decision making. Fuzzy control system is based on fuzzy inference. Fuzzy inference is a process in which mapping from input to output will be formulated based on fuzzy theory. Fuzzy logic is composed of "membership function", "fuzzy operator" and "IF-Then" rules. Fuzzy inference process has five levels: input variables fuzzification, applying AND, OR logic operators in assumptions section, assumptions to results inference, generalize the results and finally defuzzification of output [3, 18].

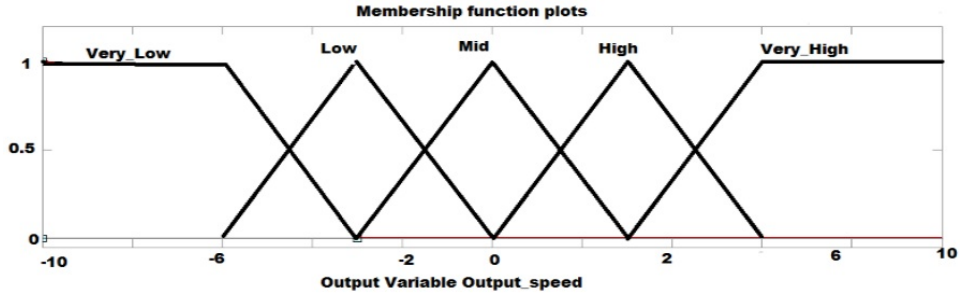
Fuzzy toolbox is embedded in MATLAB/SIMULINK that works based on Mamdani and Sugeno system. Figure 2 shows surface of inputs and output and value of these inputs and output are shown separately in Figure 3. The mechanism of fuzzy inference system is based on Mamdani system. In this structure, two inputs i.e. speed error and derivation of speed error and one output i.e. output speed are considered. Regarding final response in the induction motor, derivation of speed error is used as the second input. The importance and value of this second input is when speed error is high and when speed error is not too high, the value of the second input would be low. Based on this principle, number of rule base is defined in which for the first input there are 5 rules and for the second input there are 3 rules [1, 13]. Table 1 illustrates the relation between inputs and output that are obtained by trial and error method.



(a) Rules dataset for first input (speed error)



(b) Rules dataset for second input (derivation of speed error)



(c) Rules dataset for output (output speed)

FIGURE 2. Rules Data-Set for Inputs and Output

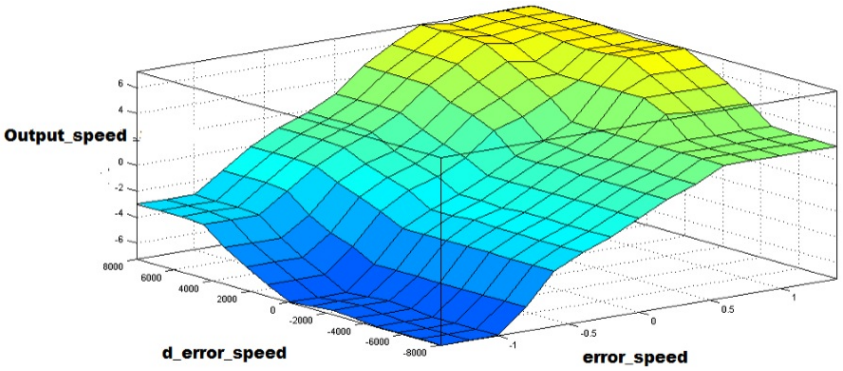


FIGURE 3. Surface of Inputs and Output

error_speed / d_error_speed	VERY_LOW	LOW	MID	HIGH	VERY_HIGH
LITTLE	Very_low	low	Mid	high	high
MID	Very_low	low	Mid	high	Very_high
VERY	low	mid	High	Very_high	Very_high

TABLE 1. The Relation between Inputs and Output

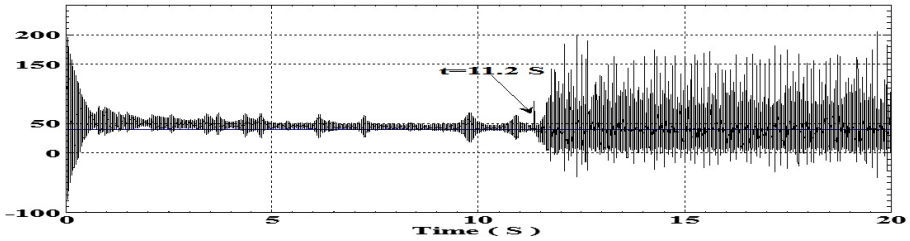
4. **Simulation**

In this section, simulation is performed on a three-phase induction motor with description in Table 2. The simulation is performed in MATLAB/SIMULINK which is carried out by using two different controllers i.e. PI and fuzzy controllers. The parameters of PI controller are also presented in Table 2. These parameters are selected based on the requirements of the application.

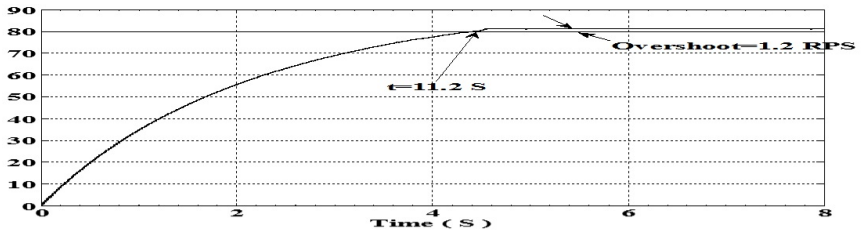
Rs (Ω)	0.087	Power (W)	5000
Rr (Ω)	0.228	Pole	4
Lls (H)	0.8 e-3	moment of inertia (kg.m2)	1.66
Llr (H)	0.8e-3	Voltage (V)	300
Lm (H)	34.8e-3	Phase	3
Kp	1000	KI	4

TABLE 2. Specification of Three-Phase Induction Motor [1]

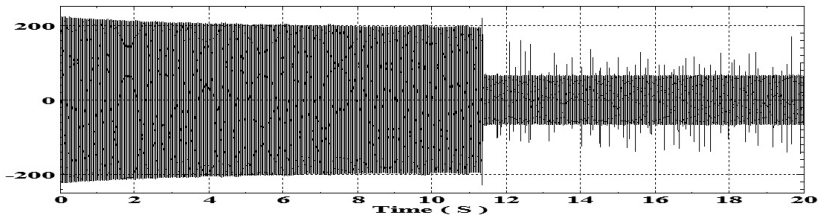
4.1. **Simulation with PI Controller.** Simulation results for this case are shown in Figure 4. Output torque is shown in Figure 4.a which has ripple in steady-state condition. Speed of motor is shown in Figure 4.b which is stabilized after 11.2 seconds and three-phase current of motor is shown in Figure 4.c.



(a) Output torque of motor



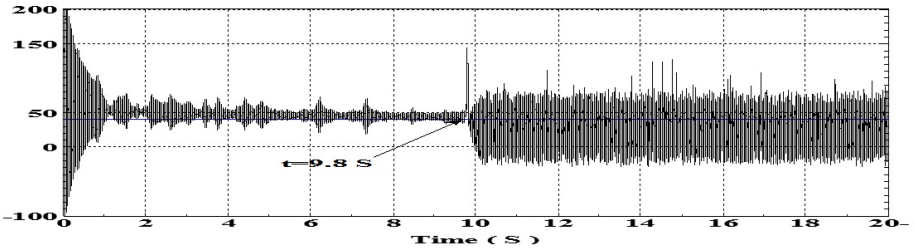
(b) Speed of motor



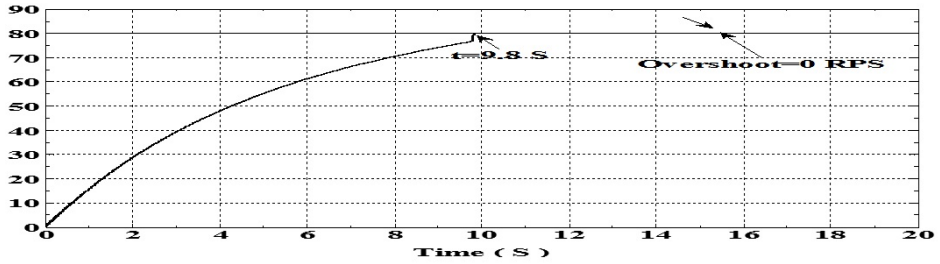
(c) Three-phase current of motor

FIGURE 4. Simulation Results for Torque, Speed Control and Three-Phase Current with PI Controller

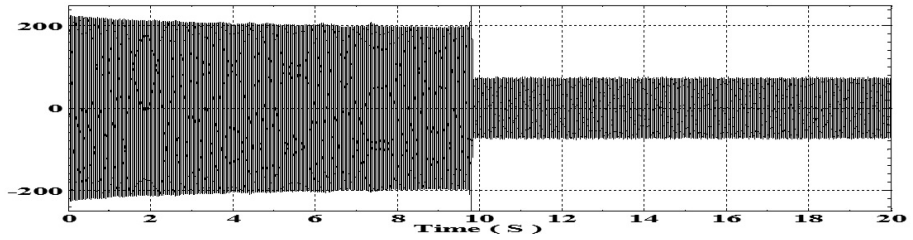
4.2. **Simulation with Fuzzy Controller.** In this section, PI controller is replaced by fuzzy controller. Simulation results of this case are shown in Figure 5. Output torque is shown in Figure 5.a which has fewer ripples in steady-state condition compared with PI controller. Speed of motor is shown in Figure 5.b which is stabilized after 9.8 seconds and three-phase current of motor is shown in Figure 5.c.



a) Output torque of motor



b) Speed of motor

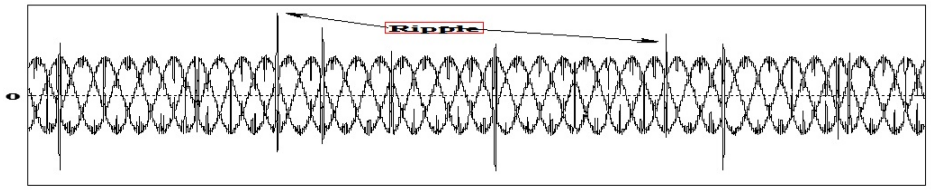


c) Three-phase current of motor

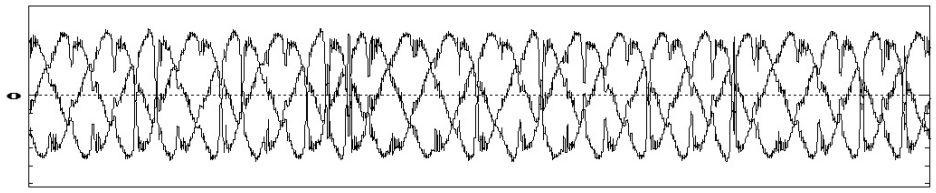
FIGURE 5. Simulation Results for Torque, Speed Control and Three-Phase Current with Fuzzy Controller

4.3. **Comparison between PI and Fuzzy Controllers.** After simulation and comparison between PI and fuzzy controller, the following results are obtained:

- The time needed for final response is very important. Fuzzy controller needs less time to reach to the final stable speed in full-load operation. In fact fuzzy controller needs only 9.8 s (Figure 5.b) for reaching to stable and steady-state speed while PI controller needs 11.2 s (Figure 4.b).
- Fuzzy controller has less overshoot compared to PI and Fuzzy controller reaches to final speed more accurately but final speed of PI controller has pulsations (Figures 4.b and 5.b)
- Lower ripple and reduction of harmonics in current and torque is also achieved using fuzzy controller (Figure 6). Total harmonic distortion (THD) of PI controller is 15.88 % while fuzzy has a THD of 5.75 % (Figures 7).



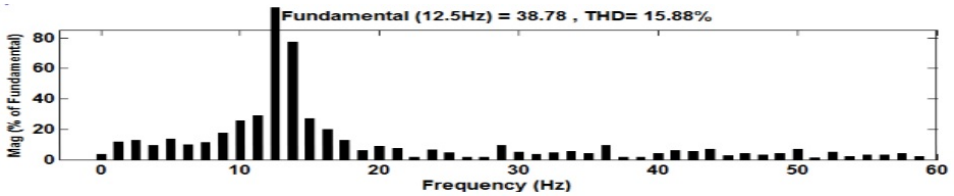
a) PI Controller



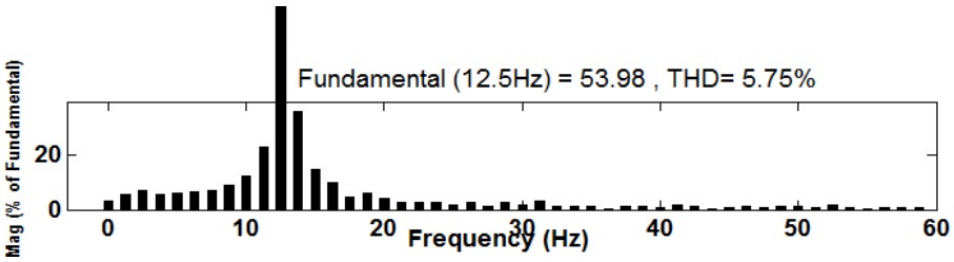
b) Fuzzy Controller

FIGURE 6. Phase Current for PI and Fuzzy Controller

Table 3 illustrates comparison between parameters of motors with PI and fuzzy controller.



a) PI controller



b) Fuzzy controller

FIGURE 7. Current THD of IM with PI and Fuzzy Controller

controller	Time for Steady-State speed (s)	Over Shoot (rps)	Current THD (%)
PI (No-load)	1.4	0.2	11.69
Fuzzy (No-load)	1.35	0	7.62
PI (loaded)	11.2	1.2	15.88
Fuzzy (loaded)	9.8	0	5.75

TABLE 3. Overall Comparison between PI and Fuzzy Controller

5. **Conclusion**

In this paper, a comparison was done between PI and fuzzy controllers for design of three-phase induction motor speed control. Utilizing fuzzy controllers instead of PI controllers improves speed control of induction motor in no-load, and full-load operation. A three-phase induction motor was considered as case study and by simulation of MATLAB/Simulink the following results are obtained:

- Using fuzzy controller in full-load operation reduces the time for final speed about 14 %.
- Ripple of current is improved about 39 %. Besides, speed overshoot in fuzzy method is minimum.
- THD of PI controller is 15.88 % while fuzzy has a THD of 5.75 %.

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