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Fuzzy Logic Based Speed Control System for Three-Phase Induction Motor

Three-phase induction motors have been used in a wide range of industry applications. Using modern technology, the speed of induction motor can be easily controlled by variable frequency drives (VFDs). These drives use high speed power transistors with various switching techniques, mainly PWM schemes. For several decades, conventional control systems were applied to electric drives to control the speed of induction motor. Although conventional controllers showed good results, but they still need tuning to obtain optimum results. The recent proposed control systems use fuzzy logic controller (FLC) to enhance the performance of induction motor drives. In this paper, a fuzzy logic based speed control system is presented. The proposed controller has been designed with MATLAB/SIMULINK software, and it was tested for various operating conditions including load disturbance and sudden change of reference speed. The results showed better performance of the proposed controller compared with the conventional PI controller.

Keywords: *Electric Drive, PI controller, Fuzzy Logic Controller*

1. Introduction

Electric drives play an important role in the field of power electronics; since they are used in a wide range of applications. In this context, it is important to match the correct drive to the application in accordance with its requirements. In the recent decades, a huge step had been taken in power semiconductors and microprocessors development. As a result, modern drive system technology had changed dramatically, and accordingly more studies were done on electric drive systems to fulfill the various needs of different applications [1].

The continuous improvements in power electronics field made it easier to develop modern switch-mode inverters based on high speed power transistors, like MOSFET and IGBT. Such inverters are able to adjust the speed of induction motor more efficiently than before. Using power transistors has the advantage of making electric drives lighter and less cost than old styles that used DC motors. Furthermore, the switching schemes, mainly PWM, improved the performance of modern electric drives, and several PWM techniques had been proposed with different advantages and drawbacks. On the other hand, induction motors became the most widely used in industrial drive applications due to their advantages over other motors. Some of these advantages are: ruggedness, lower rotor inertia, absence of commutator and brushes, besides the lower price and smaller size [2].

For several decades, researchers used classical methods to control the speed of induction motor. Such controllers (like conventional PI controller) showed simplicity in design and stability in performance. Even though, the conventional controllers still require the mathematical model of induction motor. Besides, they may produce overshoot or long settling time in case of load disturbance or sudden change of reference speed. To overcome these drawbacks, intelligent control systems, such as fuzzy logic, had been widely used for induction motor control. These control systems are based on artificial intelligence theory and conventional control theory as well [3].

In this paper, a fuzzy logic based speed control system is presented. The proposed controller is applied to electric drive to control the speed of three-phase induction motor. Section II describes the use of FLC in electric drives and some related works. Section III illustrates the architecture and simulation of intelligent controller applied to three-phase voltage source inverter. Results are shown and discussed in Section IV followed by conclusion in Section V.

2. Fuzzy Logic Control System

A. Related Works

As mentioned in Section I, PI controller is one of the most commonly used controllers showing good robustness. Later on, FLC became a well-known controller and had been used as independent or combined with PI to improve the performance of the electric drive. The use of FLC for speed control of induction motor is reviewed in the following literature survey:

Fonseca et al. [4] presented an evaluation of fuzzy logic techniques applied to the control of induction motor. Matlab/Simulink and fuzzyTECH were used for simulation, while Intel 80C196KD microcontroller was used to generate the PWM signals to control the IGBT motor drive inverter. Leão et al. [5] proposed a fuzzy speed control loop for three-phase inverter to control the speed of induction motor. To achieve a specific speed, a computer program is used to generate PWM signal which gives the corresponding frequency. Furthermore, an internal PID controller was used for current control. Baghgar et al. [6] demonstrated the use of artificial intelligent technique as a controller for induction motor. In that study, FLC was applied to test the performance the induction motor drive, which was implemented with suitable speed regulation. Chitra et al. [7] proposed a fuzzy logic based speed control of induction motor using field oriented control technique. The proposed system was designed and simulated using MATLAB. Erenoglu et al. [8] introduced a design methodology that combines PID and the fuzzy controllers to form an intelligent hybrid controller. The blending mechanism of PID and fuzzy controllers depends on a certain function of actuating error to combine. The proposed system has an intelligent switching scheme that decides about the priority of the two controller parts. A genetic search algorithm was used for tuning the controller parameters. Javadi [9] proposed the use of artificial intelligence to control induction motor. According to his study, an AC induction motor may consume more energy than it needs. So, using FLC can save more energy consumed by induction motor during start time or when it works in less than full load. Furthermore, the cost and complexity of controller are reduced. Tunyasrirut et al. [10] presented a speed control system for induction motor using SVPWM voltage source inverter. This proposed system adjusts the frequency and amplitude of the stator voltage to the control the speed of the motor, while keeping the V/f ratio constant. A Fuzzy logic controller was used to keep the motor speed constant while the load varies. Dey et. al [11] proposed a set of fuzzy logics to control the speed of vector controlled three-phase induction motor. In this study, FLC and PI controller were modeled using MATLAB/SIMULINK. Both controllers were then compared to each other based on their effect on the performance of the induction motor.

As a conclusion of the above mentioned studies, their results emphasized the following:

1. The superiority of fuzzy logic controller over PID controller.
2. The use of fuzzy logic controllers in enhancing the performance of induction motor drive.
3. The trends of using intelligent control systems in the recent studies on electric drives.

B. Applying of Fuzzy Logic to Electric Drives

Fuzzy control is based on the fuzzy logic theory which was first proposed by Zadeh [12]. Fuzzy controllers are rule-based controllers that use "if–then" format for the control process. In this format, several variables could be used either in condition or conclusion side of the "if–then" rules. As a result, the mathematical model of the system is not required in fuzzy control, so it can be applied to nonlinear systems. The structure of fuzzy controller is shown in Figure 1 [13].

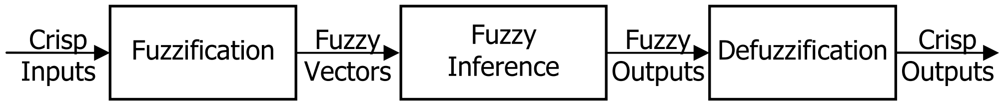

Figure 1. Fuzzy control structure

As seen in Figure 1, the fuzzy inference system consists of three main parts which can be illustrated as follows:

1. **Fuzzification**

   Fuzzification is the process in which a crisp values are transformed into grades of membership for linguistic terms of fuzzy sets. The most commonly used method is the singleton fuzzifier [14].

2. **The fuzzy inference engine**

   Fuzzy inference engine is the process that relates input fuzzy sets to output fuzzy sets using if-then rules and fuzzy mechanism to derive a reasonable output form crisp or fuzzy inputs. There are two types of fuzzy inference systems: Mamdani-type and Sugeno-type. Mamdani fuzzy inference system is the most commonly used method; since it has the advantages of intuition, wide acceptance and suitability to human input [15].

   The following steps summarize the algorithm of Mamdani (max-min) inference engine [16]:

   Step 1: Computing the degree of fulfillment by:

$$\beta_i = \max\,[\mu_{A'}(x) \wedge \mu_{Ai}(x)], i = 1,2,\ldots,K \tag{1}$$

   Step 2: Deriving the output fuzzy sets β'_i :

$$\mu_{Bi'}(y) = \beta_i \wedge \mu_{Bi}(y), y \in Y, i = 1,2,\ldots,K \tag{2}$$

   Step 3: Aggregating the output fuzzy sets β'_i into a single fuzzy set B':

$$\mu_{Bi'}(y) = \max_{1 \le i \le K} \mu_{Bi'}(y), y \in Y \tag{3}$$

3. **Defuzzification**

   Defuzzification is the process from which a crisp value is produced from a fuzzy set through fuzzy inference. Although many defuzzification methods have been proposed, they are not resting on scientific bases; so defuzzification is considered an art rather than a science [14]. The following are the most famous defuzzification methods: centroid, average of maxima, midpoint of maxima, median, area, height, and maximal height [17]. Among these methods, the most commonly used is the (centroid) defuzzification. This technique was developed by Sugeno in 1985, and it had very accurate results compared with other methods. The centroid defuzzification, which is shown in Figure 2, could be expressed as follows [18]:

$$x^* = \frac{\int \mu_i(x)\, x\, dx}{\int \mu_i(x)\, dx} \tag{4}$$

   where: x^* is the defuzzified output

   $\mu_i(x)$ is the aggregated membership function

   x is the output variable

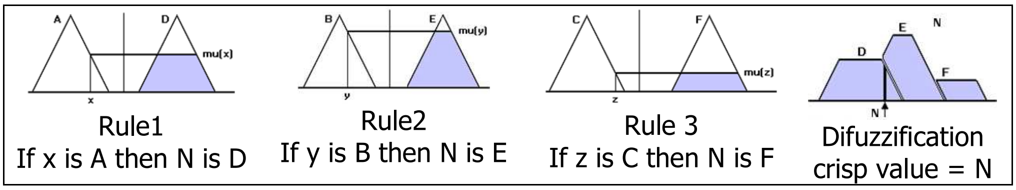

Figure 2. Centroid defuzzification using max-min inference

C. Fuzzy Logic-Based Controller

Modern electric drives require monitoring the shaft speed of the motor continuously to assure that it follows preselected tracks. Fuzzy control system could be designed to achieve this goal. Fuzzy control system could replace human experience using fuzzy rule-based system by converting linguistic control into automatic control approach. One of FLC advantages is that it shows high performance control without requiring mathematical model of the system. The implementation of FLC could be summarized in the following steps [19]:

1. Determination which of system dynamic parameters will be used as input, and which will be used as output of the fuzzy controller. For example: rotor speed and rotor acceleration are the inputs, while voltage and frequency are the outputs.
2. Choosing proper linguistic fuzzy variables to describe the membership functions for input and output variables of the fuzzy controller. These variables are used to transform numerical values into fuzzy quantities. For example: (NL) is used for (negative large), and (PM) is used for (positive medium).
3. Building the fuzzy control rules that relate input variables to output variables using (if-then) statements.
4. Finally, a fuzzy centroid is used to calculate the fuzzy control output.

D. Speed control using FLC

In the case of motor speed control, the two needed input variables for FLC are: the motor speed error (E) and its derivative, which represents the change of speed error (CE). Whereas, the controller output is the change in frequency (CF) of the voltage supply fed to motor. Speed error and change of speed error could be defined as follows:

$$E = V_{ref} - V_{act} \quad (5)$$

$$CE = dE / dt \quad (6)$$

where

V_{ref} is the desired motor speed
V_{act} is the measured motor speed

In fuzzy controller design, three main regions could be defined for each of the two input fuzzy variables, and the same number for the output variable. These regions are: negative, zero, and positive (as shown in Figure 3). In the input side (E and CE), these regions are used to determine the required frequency of voltage supply based on predefined regions at the output side (CF). Such frequency enables the motor speed to follow a desired reference track [19].

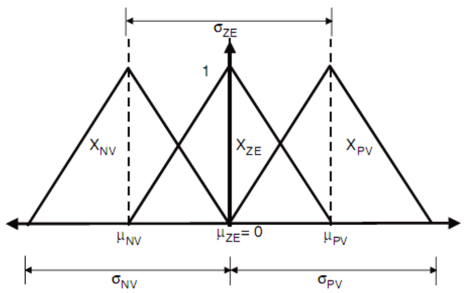

Figure 3. Triangular membership functions example

Positive and negative regions are usually divided into sub regions, such as (positive big) and (negative medium). In general, an odd number of membership functions are used to partition a region in fuzzy logic applications, often five or seven [18].

3. Description of the Proposed Intelligent Controller

The proposed control system (as shown in Figure 4) has two inputs: the first input is the set point, which represents the desired speed of motor. The second input is the feedback signal, which represents the actual motor speed. FLC was applied to this system to control the speed of the induction motor. The output of FLC is sent to the three-phase inverter to produce waveform with variable voltage and frequency to control the speed of the induction motor.

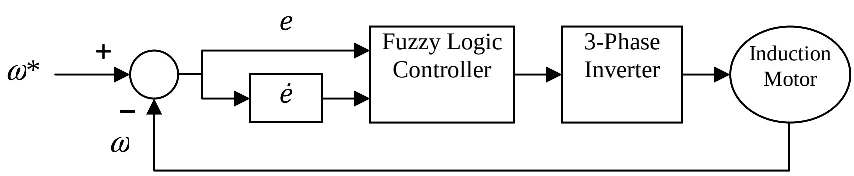

Figure 4. Block diagram of fuzzy logic based speed control system

FLC in this system uses Mamdani fuzzy inference system to relate two input variables to one output variable. The first input variable is the error (E), which is the difference between desired (set point) and measured speed, while the other input is the change of error (CE). The output variable is the change in frequency (CF). The membership functions for input and output variables are shown in Figure 5 and Figure 6.

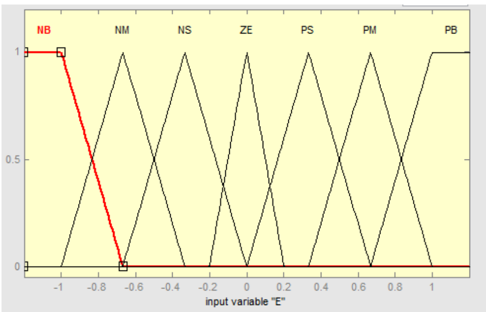

Figure 5. Membership functions of speed error (E) and change in frequency (CF)

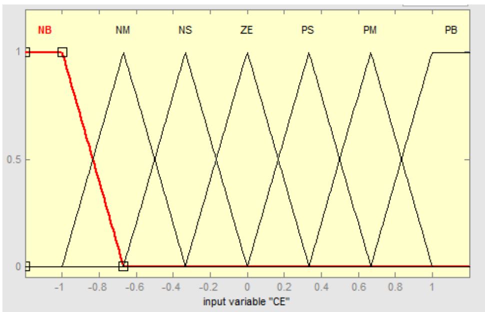

Figure 6. Membership functions of change in error (CE)

All input and output variables were normalized to be fit the range of (-1 to 1). The output variable (CF) is used to calculate the needed change of frequency which will be used to control the speed of induction motor. All fuzzy rules used in the proposed system are summarized in Table 2:

Table 2. Fuzzy rule base of FLC

E \ CE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The combination of three-phase inverter with FLC block yields a closed loop fuzzy control system for induction motor drive as shown in Figure 7.

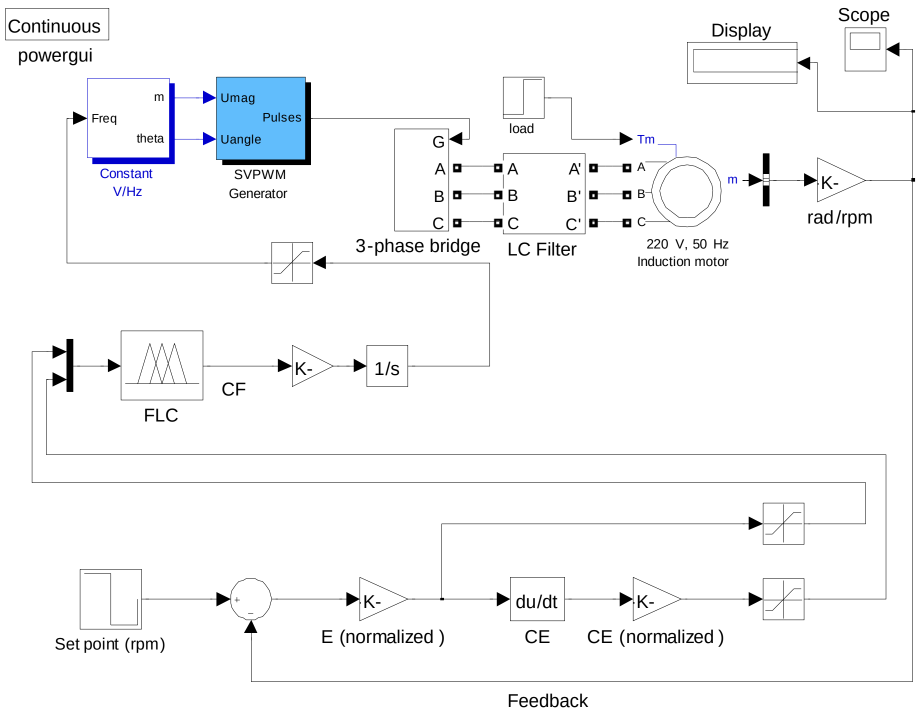

Figure 7. Fuzzy logic controller for three-phase induction motor drive

As shown in Figure 7, set point is the desired speed of the motor, while the feedback signal is the measured value of the induction motor speed. The measured speed is multiplied by (30/π) to convert the (rad/s) unit into (rpm) unit. The error signal (which is the actual speed subtracted from the desired speed) and its derivative are used as input for FLC block. The output of FLC is the required change in frequency which will be integrated continuously, while the saturation block is used to limit the output frequency within the system limitations.

The control signal, which represents the frequency in this case, is sent to V/Hz block which will maintain a constant ratio between voltage and frequency to keep the torque constant while the speed varies. The output of this block is sent to SVPWM generator which will accordingly produce a PWM signal that meets the input frequency. Resulted PWM signal is used to trigger the MOSFET Hex-bridge to produce a similar signal with amplified voltage in the inverter output.

Eventually, LC-filter smoothes the output wave to remove high frequency signals and produce a sine wave output voltage with the fundamental frequency. This wave will be used to drive the motor in the desired speed. Feedback signal, which is the motor speed, will be sent again to FLC. So, the closed loop control system works continuously to achieve the desired motor speed, and keep it stable.

4. Results and discussion

Several simulation tests were done using both PI and FLC to control the speed of induction motor. Simulations were carried out using various operating conditions such as reference speed and applied load. The performance of PI and FLC were analyzed and compared.

The following two figures illustrate the speed response of FLC for selected reference speeds and its performance during load disturbance.

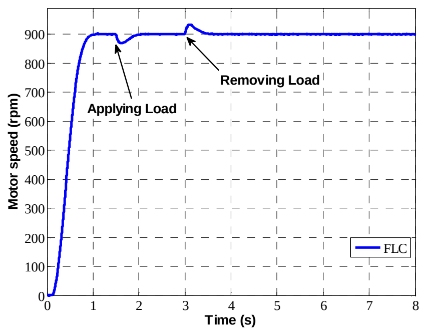

Figure 8. Speed response (900 rpm)

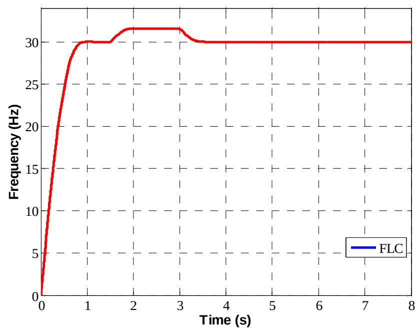

Figure 9. Control signal (900 rpm)

Figure 8 shows the speed response of the proposed control system when the reference speed = 900rpm, while Figure 9 shows the output of FLC (the control signal). In this simulation, a load was applied at time = 1.5 s, then it was removed at time = 3 s. The applied load caused the motor speed to go down below the reference speed. At the same time, the control signal went up to compensate the loss of speed as shown in Figure 9. When the applied load was removed, the control signal went down to maintain the actual speed equal to the set point.

The following two figures show the speed response of FLC system while applying two loads with time interval between them.

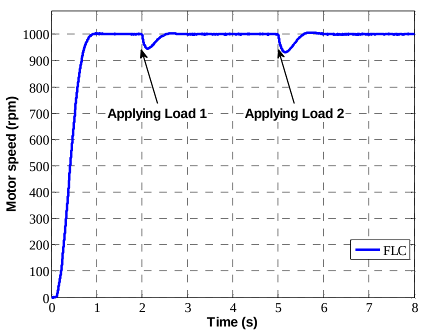

Figure 10. Speed response (1000 rpm)

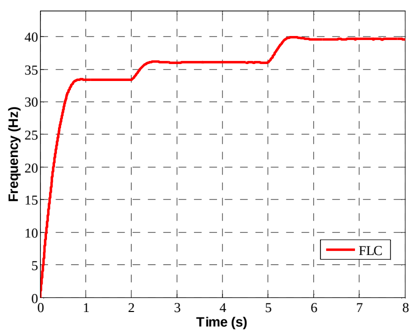

Figure 11. Control signal (1000 rpm)

As seen in Figure 10, load 1 was applied at time = 2 s, while load 2 was applied at time = 5 s. Since load 2 is greater than load 1, its effect on the motor speed is greater. Consequently, the control signal is proportional to load disturbance as seen in Figure 11. So, the actual motor speed is maintained equal to the reference speed after a short time of change because of load disturbance.

For comparison, the following simulation tests show the speed response of the system while using FLC and PI for various reference speed and applied load.

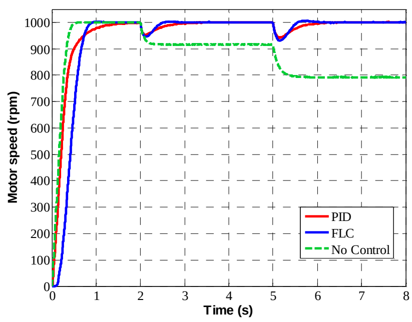

Figure 12. Speed response comparison for sudden change in load

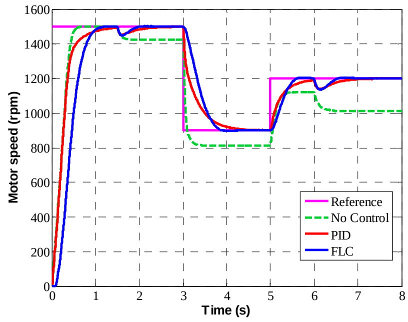

Figure 13. Speed response for sudden change in load and reference speed

Figure 12 shows a comparison of system behavior (without control, with PI and with FLC) while applying load at time = 2 s and another load at time = 5 s. In Figure 13, multi reference speeds (1500, 900 and 1200 rpm) were used with load disturbance at time = 3 s and at time = 5 s. As noticed in the both figures, the actual speed went down after each load applying, while both PI and FLC showed a good response to this change. But, to be more accurate, Table 3 shows a numerical comparison between the performance of FLC and PI, in terms of rise time and settling time, when multistep speed input is used as shown in Figure 13.

Table 3. A comparison of FLC and PI performance in multistep speed response

Reference speed (rpm)	Rise time (s)		Settling time (s)	
	FLC	PI	FLC	PI
1500	0.5392	0.4026	0.9496	0.9685
900	0.5387	0.6476	0.8074	1.1844
1200	0.3850	0.5201	0.5736	0.8461

It is clear from the above table that except for the rise time at 1500 rpm, FLC showed faster response in both rise time and settling time compared with PI response for multistep speed input. As a result, FLC showed better performance compared with PI controller. FLC also showed the ability to control speed of the three-phase induction motor and provide an accurate and fast response with relatively no overshoot and no steady state error.

Finally, the quality of the output waveform depends on the smoothness of the sine wave which depends on the harmonic components. So, it is essential to analyze the harmonic components to determine the quality of the inverter output waveform. For this purpose, several tests were done using simulation to analyze the harmonic components of the output voltage. A sample test was done using the following input speeds: 700, 900, 1200 and 1400 rpm, and the resulting THD was 2.3%, 2.9%, 1.8% and 3% respectively. So, all THD values are less than 5%, which is the acceptable harmonic distortion according to IEEE standards [20].

5. Conclusion

This paper presents a fuzzy logic based control system used for controlling the speed of three-phase induction motor. The structure of fuzzy logic controller was described in this paper, in addition to reviewing some related works. The closed loop control system of FLC and three-phase voltage source inverter was simulated using SIMULINK software. Based on the set point and feedback, FLC produces the proper control signal which will be used by the inverter to control the speed of the induction motor. Simulation results showed better performance of the proposed FLC over the conventional PI controller in both rise time and settling time.

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