
INVESTIGATION OF SPEED CONTROL PERFORMANCES OF THE FUZZY LOGIC CONTROLLERS HAVING DIFFERENT MEMBERSHIP FUNCTIONS AND INFERENCE METHODS

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ABSTRACT

Alternative current motors are generally modelled with constant system parameters. However, parameters of the motor show variations during operation due to complex, unidentified and nonlinear system dynamics. Fuzzy logic controllers are widely used as a solution to overcome this problem. Because, fuzzy logic controllers don't be affected from model uncertainties of the system to be controlled. In this study, permanent magnet synchronous motor that is one of the alternative current motors is controlled with fuzzy logic controller. All stages of the designed controllers are developed by using unique softwares instead of ready toolboxes. Triangular and trapezoidal membership functions with Mamdani and Larsen inference methods are used in the designed fuzzy logic controllers. Speed control performances of the fuzzy logic controllers have been investigated and compared with each other in the simulation studies. According to the obtained results from simulation studies, it is observed that fuzzy logic controllers designed with Larsen fuzzy inference method and trapezoidal input membership function provides better performance.

Keywords: Permanent magnet synchronous machine, Fuzzy Logic, Fuzzy Inference Methods

1. INTRODUCTION

Alternative current motors that is an indispensable part of our daily life, has a fairly wide and common using area. Alternative current motors are generally considered in two main groups as synchronous and asynchronous. Asynchronous motors are the most used type of electric machines in industrial systems. But, asynchronous motors couldn't provide the desired sensitivity and torque smoothness at low speed applications. In order to operate the asynchronous motor at low speeds additional systems such as reducers are needed. This situation adds extra cost, and it also prevents achieving the desired efficiency from the motor.

Depending on these mentioned problems of asynchronous motors, there has been an increase in the tendency towards motors that can operate with high efficiency in industrial applications that need to work at a wide range of speeds. Permanent magnet synchronous motors (PMSM) have been become very popular for industrial applications due to their high power density, high efficiency, low size and ability to operate over a wide range of speeds [1-3]. Especially since the last quarter of the 20th century, with the improvements in magnet technology the use of permanent magnet synchronous motors has increased even more in industrial applications.

PMSM and similar type of alternative current motors are generally modelled with constant parameters. But, winding resistances of the motor vary with temperature, and the inductances of the motor vary due to magnetic saturation during operation. In addition, there are machine dynamics that are not linear and can not be modeled in the motor structure. These mentioned problems are causing model uncertainty in the system to be controlled. Artificial intelligence control methods are developed as a

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solution for the problem mentioned above. Fuzzy logic, artificial neural networks and heuristic algorithms are some of the popular artificial intelligence control techniques. Fuzzy logic that is one of these methods were used for controlling of PMSM by many researchers. Field oriented control of PMSM [4], controlling of PMSM under different operating conditions [5], speed control of PMSM [6-8], vector control of PMSM [9], direct torque control of PMSM [10-11], controlling PMSM with fuzzy logic controllers having different membership functions [12], controlling PMSM with fuzzy logic controllers having different rule sizes [13-14] are some of these studies. Membership functions and inference methods are important parts of the fuzzy logic controllers, directly affect the performance of the controller. For this purpose, speed control of the permanent magnet synchronous motor is performed with fuzzy logic controllers having both different inference methods and different input membership functions in this study. Fuzzy logic controllers are designed by using unique softwares and accordingly simulation studies are performed.

The paper is organized as in five sections. Section 2 presents the mathematical modeling of PMSM. Section 3 presents the fuzzy logic controller. Section 4 presents the simulation studies. Section 5 has the conclusions.

2. PMSM MODELING

There are three different mathematical model used for modeling of PMSM. These are three phase abc reference model, d-q reference model and two dimensional α - β reference model respectively. Conversions of these reference models between themselves is made by using Clarke and Park transformations. By using the Clarke transformation, the magnitudes of the three phase stator reference frame are transformed into a two dimensional α - β reference frame. By using the Park transformation, the sizes of the two dimensional α - β reference frame are transformed into the d-q rotor reference frame. d-q and α - β references are made up of perpendicular axes to each other. With the transformation processes, rotating magnetic field based electric machines are likened to direct current machines and their analysis and control are facilitated [1,3].

In the analyzes and simulation studies, d-q rotor reference model of PMSM is used. Two dimensional d-q rotor reference model is obtained by transferring the stator values to the rotor plane. This obtained model is similar in structure to an external excitation DC motor. d-q rotor reference equivalent circuit of PMSM is seen in the Figure 1.

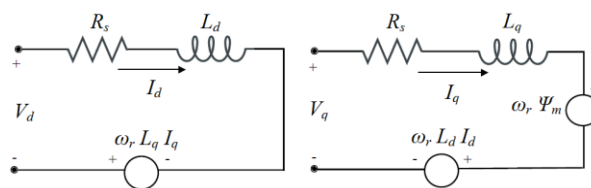


Figure 1. PMSM d-q rotor reference equivalent circuit [3]

Where, V_d and V_q are d-q component of the stator voltage, I_d and I_q are d-q component of the stator current, L_d and L_q are d-q axis synchronous inductances, R_s is the synchronous resistance, Ψ_m is magnetic flux of the permanent magnet, ω_r is angular velocity of rotor. The voltage equations for the equivalent circuit can be expressed as follows [1].

$$V_d = R_s i_d + \frac{d}{dt} \Psi_d - \omega_r \Psi_q \quad (1)$$

$$V_q = R_s i_q + \frac{d}{dt} \Psi_q + \omega_r \Psi_d \quad (2)$$

In the equation (1) and (2), equivalent magnetic fluxes of d-q reference axis Ψ_d and Ψ_q are expressed as follows.

$$\Psi_d = L_d i_d + \Psi_m \quad (3)$$

$$\Psi_q = L_q i_q \quad (4)$$

When (1)-(4) equations are used together, d-q axis voltages are obtained as follows.

$$V_d = R_s i_d + \frac{d}{dt} (L_d i_d + \Psi_m) - \omega_r (L_q i_q) \quad (5)$$

$$V_q = R_s i_q + \frac{d}{dt} (L_q i_q) + \omega_r (L_d i_d) + \omega_r (\Psi_m) \quad (6)$$

The torque of the motor depends on d-q axis current components, equivalent magnetic flux and total pole number of the motor.

$$T_e = \frac{3p}{2} (\Psi_d i_q - \Psi_q i_d) \quad (7)$$

In the equation (7), if current and magnetic flux expressions are organized again, torque of the motor will be as follows.

$$T_e = \frac{3p}{2} ((L_d - L_q) i_d i_q + \Psi_m i_q) \quad (8)$$

Depending on the torque equation of the motor, the dynamic equation can be expressed as follows.

$$T_e = T_L + B\omega_r + J \frac{d}{dt} \omega_r \quad (9)$$

Where, T_L denotes torque of the load, B denotes the coefficient of friction and J denotes the inertia torque. If (1)-(9) equations are organized together, state space equations of the motor will be obtained as follows [1].

$$\dot{i}_d = \frac{1}{L_d} (V_d - R_s i_d + \omega_r L_q i_q) \quad (10)$$

$$\dot{i}_q = \frac{1}{L_q} (V_q - R_s i_q - \omega_r L_d i_d - \omega_r \Psi_m) \quad (11)$$

$$\dot{\omega}_r = \frac{T_e - T_L - B\omega_r}{J} \quad (12)$$

3. FUZZY LOGIC CONTROLLER

The concept of fuzzy logic modeling was first introduced by L.A. Zadeh [15]. Fuzzy logic controller is structurally consisted of fuzzification, rule based inference mechanism and defuzzification units [15-16]. General structure of the fuzzy logic controller is illustrated in Figure 2.

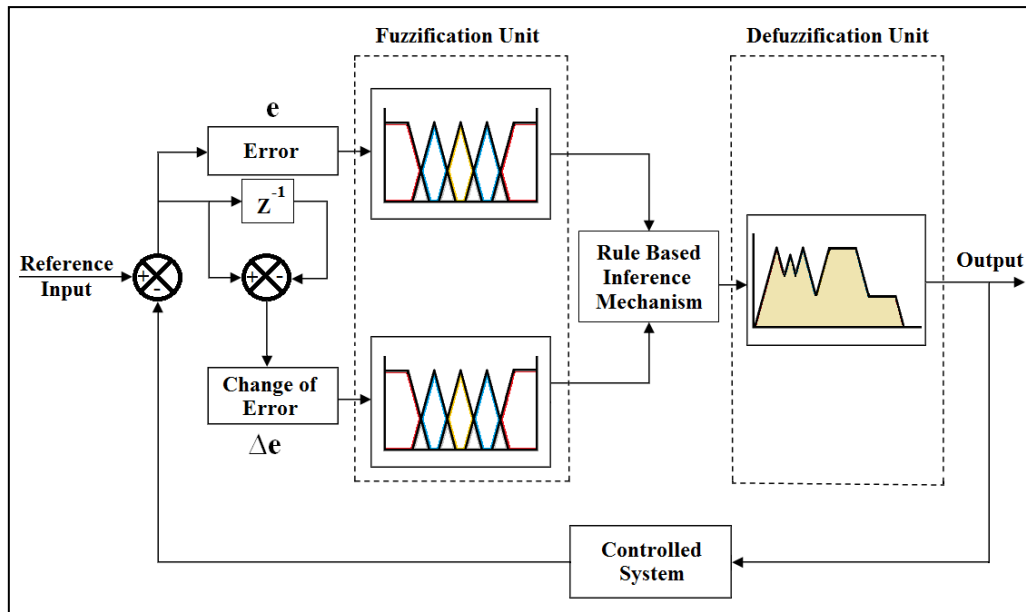


Figure 2. General structure of the fuzzy logic controller

In the fuzzification unit, membership grades in the range of membership functions (0-1) corresponding to the value of the input variables are determined. In the rule based inference mechanism unit, the membership grades coming from the fuzzification unit are evaluated according to verbal rules to obtain fuzzy results. Each rule in this unit provides a control that corresponds to a specific part of the system to be controlled. By using all rules together, a rule base expressing the whole system model is revealed [16]. The sum of the fuzzy expressions coming from the rule based inference mechanism in the defuzzification unit is converted into numerical expressions that could be applied to the system.

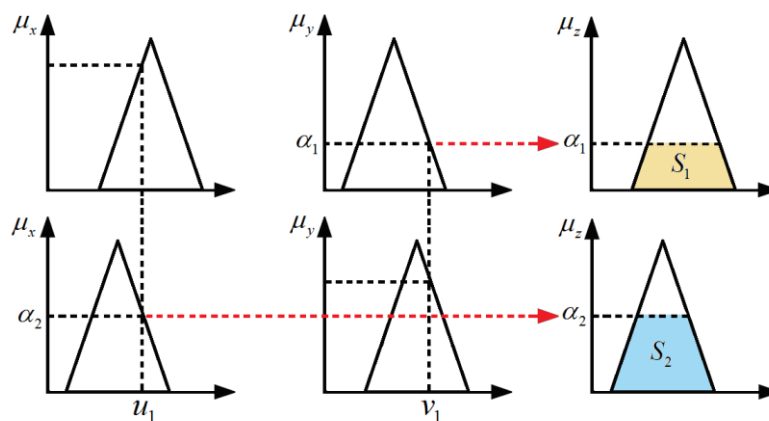


Figure 3. Mamdani fuzzy inference method

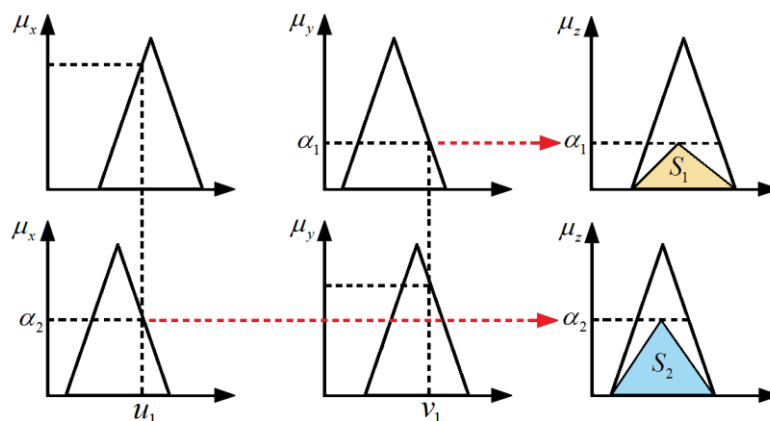


Figure 4. Larsen fuzzy inference method

In the Figure 3 and 4, the verbal fuzzy expressions coming from the fuzzification unit are transferred to the appropriate output membership function using different fuzzy relation operations. In the Mamdani inference method, the membership grades coming from the fuzzification unit are associated with the output membership function using the minimum relation operator. In the Larsen inference method, the membership grades coming from the fuzzification unit are associated with the output membership function using the algebraic product operator. Fuzzy relation operators used in Mamdani and Larsen inference methods are expressed in equations (13) and (14) respectively [17].

$$Z_i = (\mu_{xi}(u) \cap \mu_{yi}(v)) \cap \mu_{zi}(w) \quad (13)$$

$$Z_i = (\mu_{xi}(u) \cap \mu_{yi}(v)) \times \mu_{zi}(w) \quad (14)$$

Where, μ_x and μ_y denote input membership functions, μ_z denotes output membership functions, Z denote inference result and i denote rule sequence. In the inference mechanism, the total result to be obtained for k rules can be expressed as a combination of all the inference values as follows.

$$Z = \bigcup_{i=1}^k Z_i \quad (15)$$

The weighted average method is used in the defuzzification unit of the controller. The result obtained here is the digital control signal to be applied to the system. The calculation method that placed in equation (16) is used for the defuzzification process [17].

$$Z_{output} = \frac{\sum_{i=1}^n \alpha_i Z_i}{\sum_{i=1}^n \alpha_i} \quad (16)$$

Input and output membership functions of the designed fuzzy logic controllers are shown in Figure 5 and 6.

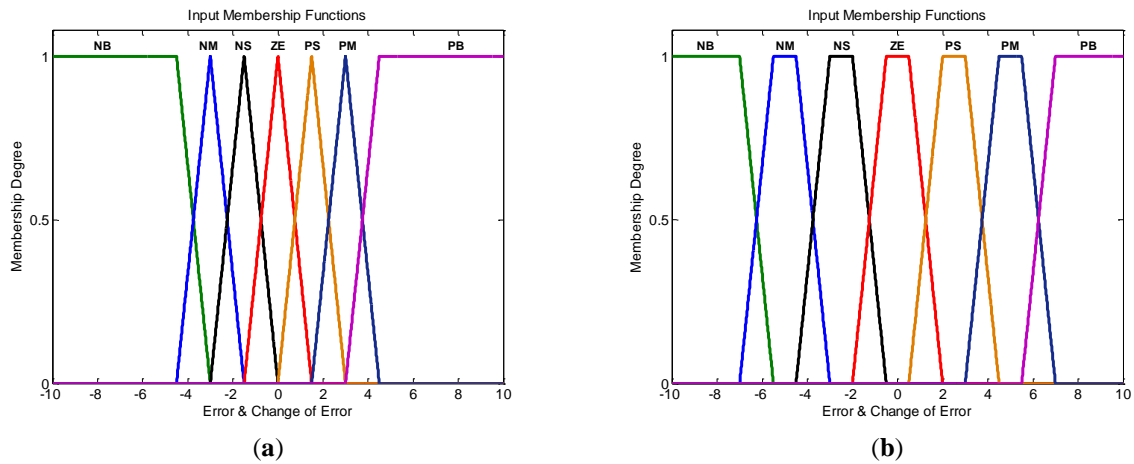


Figure 5. (a) Triangular Input Membership Functions; (b) Trapezoidal Input Membership Functions

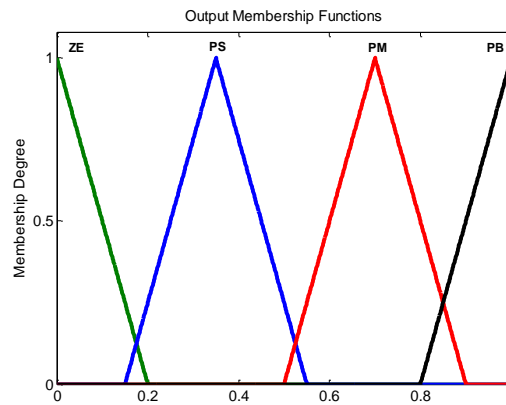


Figure 6. Output Membership Functions

As shown in Figure 5 (a)-(b), in order to avoid any loss in data space, the sum of the values at all points along the vertical axis of the input membership functions is kept equal to one. In the output membership functions, the output intervals determined in order to perform the desired expert control are taken into consideration. Seven different membership functions, NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZE(Zero), PS(Positive Small), PM(Positive Medium) and PB(Positive Big), were used for verbal variables. The rules used for the designed fuzzy logic controllers are presented in Table 1.

Table 1. Rule Table

Δe	NB	NM	NS	ZE	PS	PM	PB
e							
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	ZE	ZE	ZE	ZE	ZE	ZE	PS
NS	ZE	ZE	ZE	ZE	ZE	PS	PM
ZE	ZE	ZE	ZE	ZE	PS	PM	PB
PS	ZE	ZE	ZE	PS	PM	PB	PB
PM	ZE	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Error and change in error values are processed separately in the fuzzification units first. Here, obtained 14 fuzzy entry levels are transferred to the block where rule based inference mechanism and defuzzification processes are performed. In this block, first of all the values coming from the fuzzification unit are transferred to the output membership functions to obtain fuzzy output signals. These signals are defuzzified to constitute the required digital output control signal for the system to be controlled. In the Figures 7 and 8, the change of the output control parameter to be obtained depending on the error and change of error in the fuzzy logic controllers is presented in 3-D graphics. It is seen that the changes in this parameter take place in the range of 0-1 in accordance with the definition values of the output membership functions.

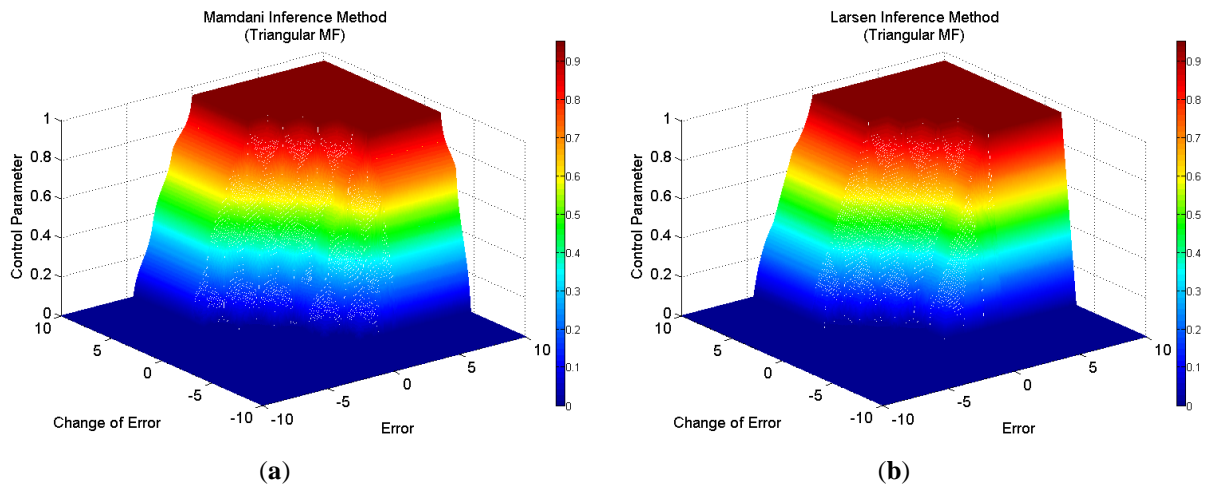


Figure 7. (a) Rule Surface (Mamdani – Triangular MF); (b) Rule Surface (Larsen – Triangular MF)

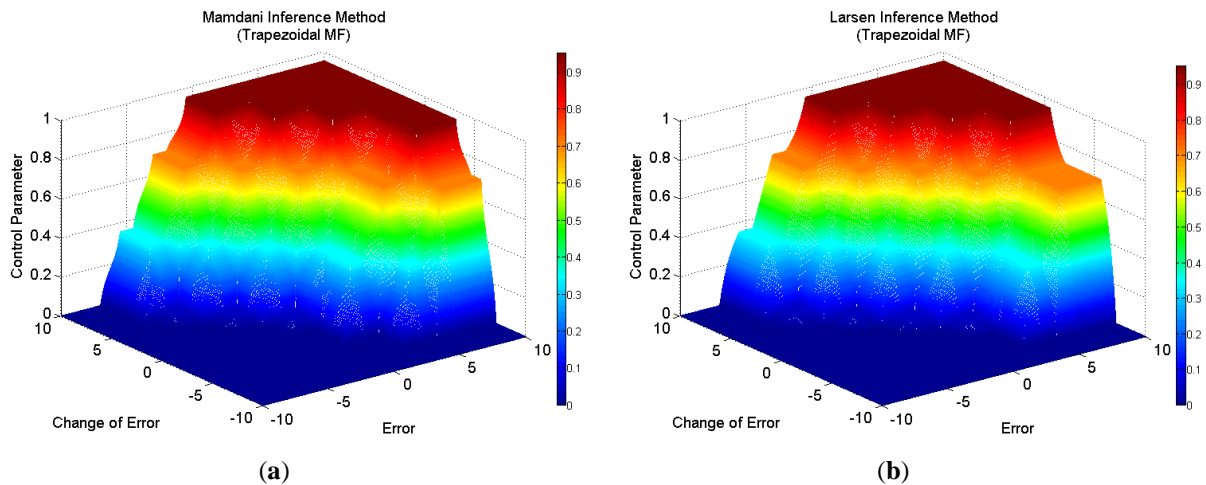


Figure 8. (a) Rule Surface (Mamdani – Trapezoidal MF); (b) Rule Surface (Larsen – Trapezoidal MF)

4. SIMULATION STUDIES

Simulation studies have been made through MATLAB / Simulink. Speed control performance of the PMSM is investigated for no load and loaded operating conditions in the studies. Performance of Mamdani and Larsen inference methods using triangular and trapezoidal input membership functions are investigated in speed control of the motor. Parameters of the PMSM used in simulation studies are presented in Table 2.

Table 2. PMSM Parameters

Parameter	Value
R_s	0.96 Ω
$L_d=L_q$	5.25 mH
B	0.0003035 Nms
J	0.00064 kgm/s ²
ψ_m	0.1827 Wb
p	4

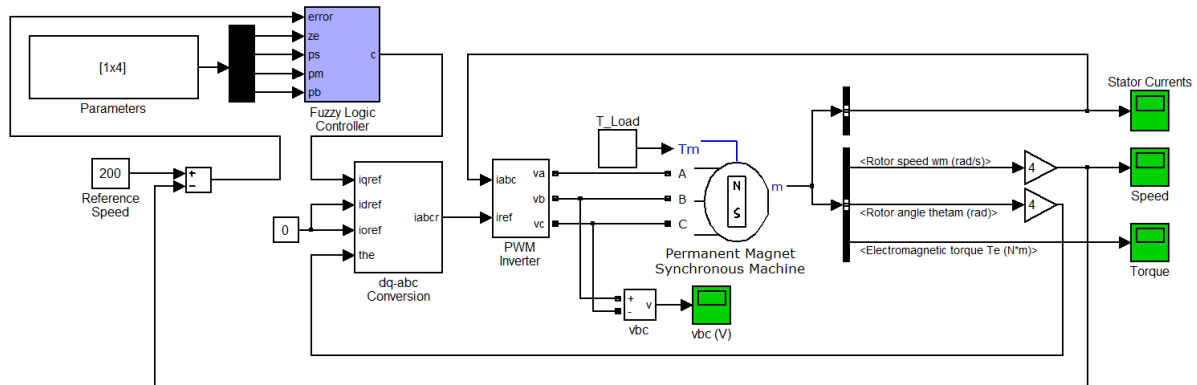


Figure 9. Simulink Circuit Used in the Simulation Studies

Block circuit used in the simulation studies is found in Figure 9. Closed loop control flowchart of the block circuit is consist of three main parts. These are fuzzy logic controller, reference model transformations and measurement block respectively. Field oriented control method for PMSM was used in simulation studies. Field oriented control is structurally based on the separation of the stator current into torque and magnetic flux components and individually the controlling of these components [18-19].

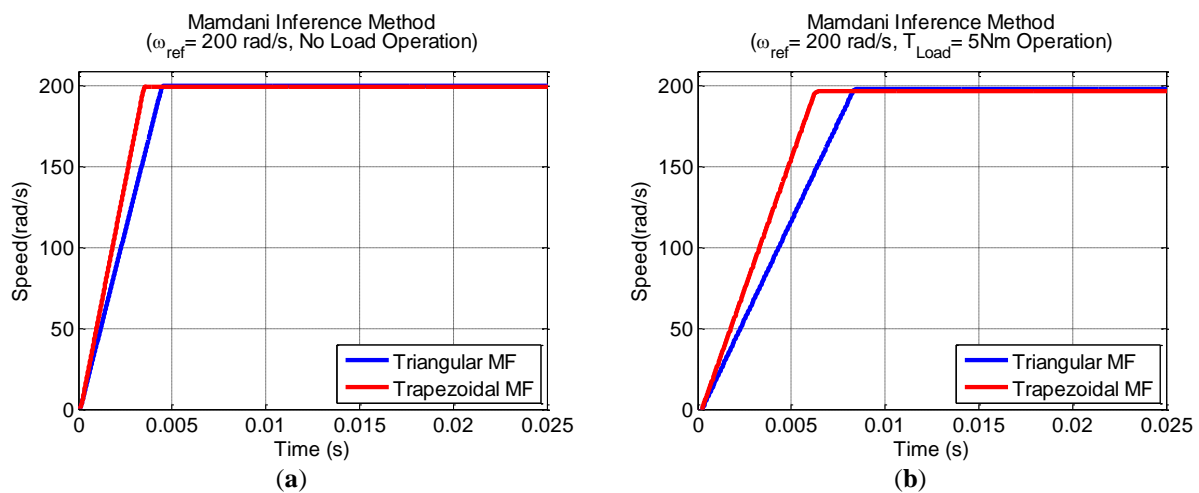


Figure 10. (a) Mamdani – No Load operating condition; (b) Mamdani – On Load operating condition

In the Figure 10(a), speed performance of the controllers designed using the Mamdani fuzzy inference method at a reference speed of 200 rad/s for no-load operating conditions are illustrated. In the Figure 10(b), speed performance of the controllers designed using the Mamdani fuzzy inference method at a reference speed of 200 rad/s for 5Nm load operating conditions are presented. It is observed that

controllers with trapezoidal input membership functions are more successful for both the no load and the loaded operation conditions and for Mamdani inference method.

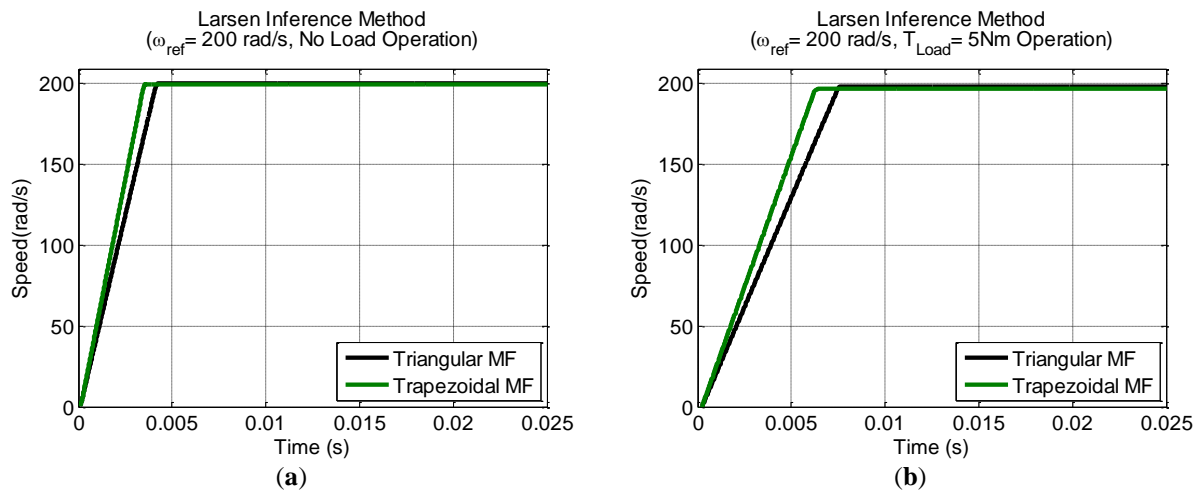


Figure 11. (a) Larsen – No Load operating condition; (b) Larsen – On Load operating condition

In the Figure 11(a), speed performance of the controllers designed using the Larsen fuzzy inference method at a reference speed of 200 rad/s for no-load operating conditions are seen. In the Figure 11(b), speed performances of the controllers designed using the Larsen fuzzy inference method at a reference speed of 200 rad/s for 5Nm loading conditions are presented. Speed changes of no-load and on load conditions are similar to graphs obtained in the Mamdani method.

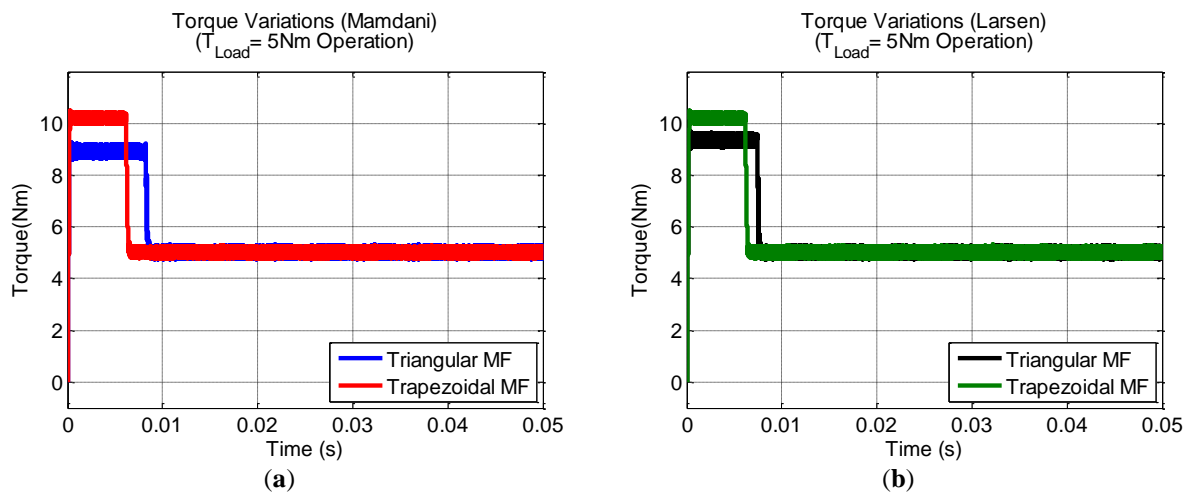


Figure 12. (a) Mamdani – Torque Variations; (b) Larsen – Torque Variations

In the Figure 12(a), torque variations of PMSM for the controllers designed using the Mamdani fuzzy inference method at a reference speed of 200 rad/s for 5Nm loading conditions are shown. Since the slope of the motor's acceleration process is constant, the torque values remain constant until the speed is arrived to reference value. In the Figure 12(b), torque variations of motor for the controllers designed using the Larsen fuzzy inference method at a reference speed of 200 rad/s for 5Nm load operating conditions are seen. Torque curve shows a similar change to motor speed position as in the controllers having Mamdani method.

5. CONCLUSIONS

In this study, fuzzy logic controllers are designed with different inference methods and membership functions. Design processes of the controllers have been realized with softwares entirely. In the studies, it is seen that all stages of the fuzzy logic controller input-output membership functions, rule based inference mechanism and defuzzification unit are worked compatible with each other.

If the effects of inference methods are evaluated, it is seen that fuzzy logic controllers having Larsen inference method has better performance than Mamdani inference method in all operating conditions. When the effects of membership functions are investigated, it is found that fuzzy logic controllers having trapezoidal membership functions has provided more successful results than triangular membership functions. And if the torque graphs are examined, it is seen that fuzzy logic controllers designed by using triangular membership functions have lower torque ripples. PMSM generates high torque at the start to satisfy the required acceleration, and then has a torque equal to the load after arriving the reference speed. When the results are evaluated in generally, it is seen that fuzzy logic controllers having Larsen fuzzy inference method and trapezoidal input membership functions has provided mostly better performances.

Effects of the membership function and inference method on performance of the fuzzy logic controller is investigated with this work. An important outcome of the work is that availability of the Larsen inference method which is not included in the MATLAB toolboxes is demonstrated. This study can be expanded with including different membership functions and inference methods for fuzzy logic controller. For the future works, it is aimed to design an improved software-based fuzzy logic controller to reduce the torque ripples. And also, It is planned to test this work in the application environment.

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