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A fuzzy logic based door position control system

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1. ABSTRACT

The position angle of a door is adjusted between closed state and full opened position at any angle using a fuzzy logic based controller. The laboratory test system consisting of a permanent magnet direct current (PMDC) motor, a gear system, a door, a power amplifier, and a fuzzy logic controller is modeled mathematically and simulated. In order to keep the door opened at any desired angle or closed, the motor is operated in forward or reversed direction. The results are compared with those of a classical PI controller for validation.

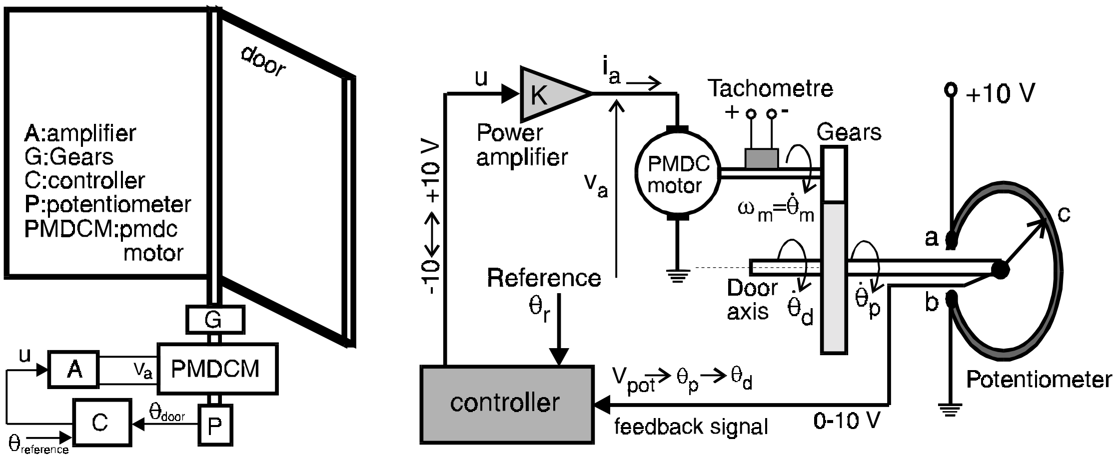
2. INTRODUCTION

Although, the scientists and engineers did not pay much attention on the fuzzy logic (FL) during the first decades of its invention by L.A. Zadeh [1], it has become a popular and useful tool in many different applications including engineering as well as social sciences during last decades [2]. Since the use of FL based linguistic approaches in control systems by Mamdani and his colleges[3], many others have started to apply FL based systems to different areas. Some of these applications related to the system control are used industry [4], in motion control of electrical motors [5.6], maximum power tracking of photovoltaic energy systems [7].

In this study, a FL based controller is designed and applied to control the position of a door, which is able to move from closed position to full opened state and from full opened position to full closed state. If an uncontrolled voltage is applied to the motor in forward direction the door opens all the way at full opened position, while an uncontrolled voltage is applied in reverse direction the door goes back into full closed position. However, the door can be kept open at any position angle by designing and using proper controllers. Therefore, a fuzzy logic controller is designed and used to control the door position. A classical PI controller is also designed to compare the results of the fuzzy logic controller for validation.

3. THE SYSTEM DESCRIPTION

A basic schematic diagram of the system to be studied is shown in Figure 1a. As it can be seen from this schematic, the system consists of a door, a gear system, a permanent magnet direct current (PMDC) motor, an amplifier, a potentiometer, and a controller.



(a) (b)

Figure 1. The system to be studied. (a) Basic schematic diagram, (b) control loop.

The control loop given in Figure 1b, may be more useful to understand how the system works. The position angle of the door is detected using a potentiometer such that the voltage ,V_{bc}, between the terminals b and c represents the door position angle in terms of potential difference. This voltage, V_{bc}, is zero when the door is closed. It is equal to 10 V, when the door is full opened, which is assumed to be 90° here. Then, the output voltage (V_{pot}=V_{bc}) of the potentiometer is used as a feedback signal to the controller and converted to degrees to be compared with a reference signal θ_r representing the desired door position in terms of degrees. The difference between the reference position angle θ_r and the door position angle θ_d generates an error signal e to be compensated by the controller. The controllers, either classical PI, PID or FL based ones, use the error signal and produce a control signal u, which is amplified by a power amplifier before being applied to the PMDC motor. If the door position is equal to the desired position, the error becomes zero resulting in a zero control signal u so that the armature voltage v_a of the motor also becomes zero.

In the design of fuzzy logic controller, the position of the door is defined by fuzzy numbers representing the linguistic terms***: closed, open a little, half open, open more than half***, and ***full open***. These linguistic terms are defined on a universe of discourse that represents the crisp values of door position angles. The controller is designed in such a way that, the door is opened or closed without any overshoot in the time response. Therefore with the command given, the door moves fast toward the target position, and slows down just before reaching the target and stops. When the door settles down at the desired position, the voltage to the motor becomes zero. It is assumed that a mechanical system is used to keep the door standstill at the desired position. Therefore, the electrical energy is used only to move the door toward the reference position, not to keep it there. If the closed position of the door is taken as 0°, then the full open position may be either 90° or 180° or any angle between 0° and 360° depending on the type of door. The full open position, here, is assumed to be 90°. Therefore, the fuzzy numbers representing the linguistic terms ***closed, open a little, half open, open more than half***, and ***full open*** are defined as given in Figure 2a.

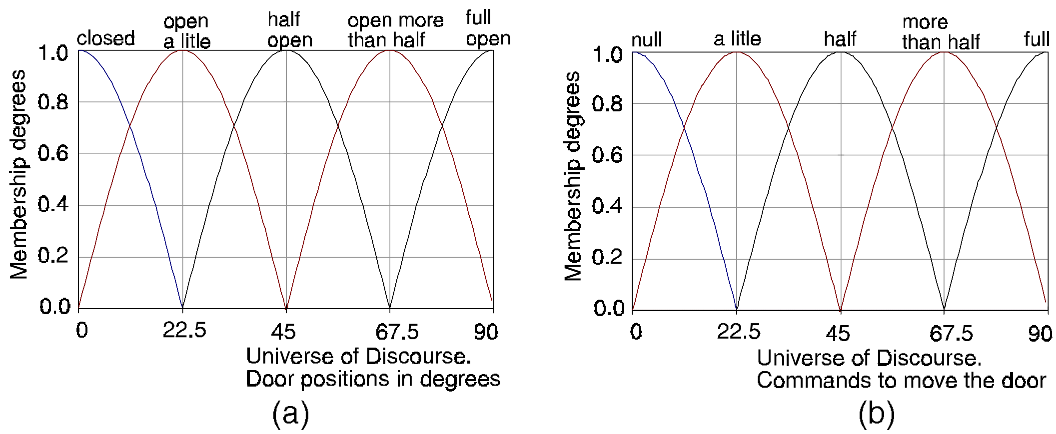


Figure 2. Fuzzy numbers representing the door position.

These definition of the linguistic terms representing the door position should not be confused with the commands that are given to change the current position of the door. For example, if we say that "The door is *open more than half*," we mean that the position angle of the door is somewhere around 67.5°. However, if we say "*Open a little.*" as a command to change the position of the door when it is half opened, we mean that we want the door change its position in an amount of about 22.5° and move toward the position defined as *open more than half*, which is represented by the numbers close to 67.5°. Therefore, it will be more convenient and more general naming the fuzzy numbers given in Figure 2a as **null, a little, half, more than half,** and **full** by omitting the words **closed** and **open** to obtain Figure 2b. Thus, it will be possible to use the same fuzzy variables given in Figure 2b to represent both door positions and commands given to change the position. The differences on the use of fuzzy subsets given in Figure 2b are listed in Table 1, which also describes the functions used to represent the linguistic terms.

The reference signal to the controller in Figure 1b is the desired position angle of the door. This new door position is either entered directly or obtained by adding or subtracting the desired amount of change in position from the current door position angle. The desired change in position angle is one of the commands given in Table 1.

Table 1. Linguistic terms representing the positions and commands.

Fuzzy subsets	Functions	positions	commands
null	numbers close to 0	full closed	no action (zero change)
a little	numbers close to 22.5	opened a little	open a little / close a little
half	numbers close to 45	half opened	open half / close half
more than half	numbers close to 67.5	opened more than half	open more than half / close more then half
full	numbers close to 90	full opened	full open / full close

After the new position of the door is entered or determined, it is compared with the current position to yield an error that is compensated by the controller. Depending upon the position error signal, the controller generates a control signal that is amplified by a power amplifier and applied to the motor. If the position error signal is positive, then a positive control signal is generated to open the door more by increasing the position angle. If the error signal is negative, then a negative control signal is generated to decrease the door opening. If the error signal is zero, then the generated control signal will also be zero so that the door remains standstill. The generation of the control signal by the controller is given next.

4. FUZZY LOGIC CONTROLLER (FLC)

An FLC operates in the same way as a human operator does. It performs the same actions by adjusting the input signal looking at only the system output. An FLC consists of three sections namely *fuzzifier, rule base*, and *defuzzifier* as shown in Figure 3. Two input signals, error and change in error, to the FLC are converted to fuzzy numbers first in fuzzifier. Then they are used in the rule table to determine the fuzzy number of the output control signal u(k). Finally the resultant fuzzy numbers representing the controller output are converted to the crisp values in defuzzifier.

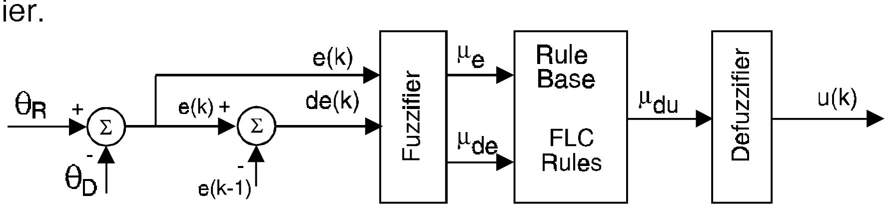
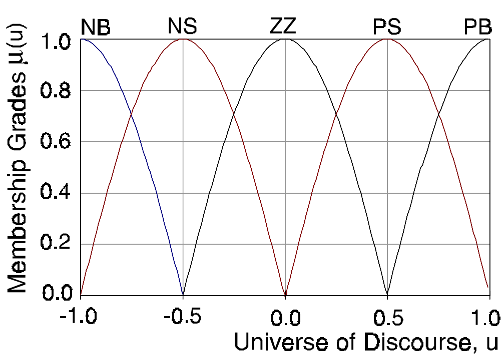


Figure 3. The structure of a FL controller.

The error signal, e, the rate of its change, de, and the control signal, u, are characterized by Five different fuzzy sets representing linguistic fuzzy variables *negative big* (NB), *negative small* (NS), *zero* (ZZ), *positive small* (PS), and *positive big* (PB). The shapes of these fuzzy sets were chosen as cosine and sine functions, and are given in Figure 4a and b for the control signal u. The shapes of the fuzzy subsets NB, NS, ZZ, PS, and PB are all the same for error, e, change in error, de, and control signal, u. However, the minimum and the maximum boundaries of the universes of discourses are different for three of them. Since the position angle of the door is assumed to be between 0 and 90 degrees (or 0 and $\pi/2$ rad), the error between these two position angles may vary from -90° to +90°, or in radians, from $-\pi/2$ to $+\pi/2$ rad. Therefore the minimum and the maximum limits of the universe of discourse for error, e, are taken as $e_{min}=-\pi//2$ and $e_{max}=+\pi/2$, respectively. After simulating the system without any controllers, it was observed that, the change in error was very small compared to the error. Therefore, the minimum and the maximum limits of the error change are assigned as $de_{min}=-\pi/50$ and $de_{max}=+\pi/50$, in order to make the changes in error more effective in terms of controller. The minimum and the maximum values of the control signal are -1 and +1, respectively as shown in Figure 4. In fact, these minimum and maximum values of the control signal are normalized values corresponding to -10 and +10, respectively. Since the control signal from the control is shown to be between -10 and +10 V in Figure 1b, the final normalized value of the control signal obtained between -1 and 1 must be multiplied by 10 in order to get the real values. The reason limiting the maximum values of input / output signals to the controller at 10 V is due to the hardware limitations of the computer that is used to implement the FLC. The simulation is also established on the same procedure so that more accurate results can be obtained. Figure 4 also shows the locations and mathematical expressions of the fuzzy subsets in the universe of discourse, u. The locations of the fuzzy subsets in the universes e, and de can be determined with the same approach. Only the min. and max. values of e and de must be used.



(a)

$$\mu_{NB}(X)=\begin{cases} 1 & \text{if} \quad X \le -X_{max} \\ |\cos(\omega X)| & \text{if} \quad -X_{max} < X \le -(X_{max}/2) \\ 0 & \text{otherwise} \end{cases}$$

$$\mu_{NS}(X)=\begin{cases} |\sin(\omega X)| & \text{if} \quad -X_{max} < X \le 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\mu_{ZZ}(X)=\begin{cases} |\cos(\omega X)| & \text{if} \quad (-X_{max}/2) < X \le (X_{max}/2) \\ 0 & \text{otherwise} \end{cases}$$

$$\mu_{PS}(X)=\begin{cases} |\sin(\omega X)| & \text{if} \quad 0 < X \le X_{max} \\ 0 & \text{otherwise} \end{cases}$$

$$\mu_{PB}(X)=\begin{cases} 1 & \text{if} \quad X \ge X_{max} \\ |\cos(\omega X)| & \text{if} \quad (X_{max}/2) < X \le X_{max} \\ 0 & \text{otherwise} \end{cases}$$

(b)

Figure 4. Fuzzy subsets and their mathematical expressions for du.

In the mathematical expressions of Figure 4b, X represents one of the crisp variables e, de, or u. $\omega = (\pi/X_{max})$ is the cycling frequency of sine and cosine functions.

For every kth sampling instant, the position angle of the door and reference are compared to determine the error signal e(k). Then, this error e(k) and its change de(k)=e(k)-e(k-1) from previous sample to the current sample are inputted to the fuzzifier. After the fuzzy numbers representing e(k) and de(k) are obtained, the fuzzy number of u(k) is determined using the assignments given in rule decision table, which defines the control actions to be taken. Since there are five fuzzy membership functions for e(k) and de(k), a rule decision table with 25 rules is formed as in Table 2.

Table 2. The rule decision table

	NB_{de}	NS_{de}	ZZ_{de}	PS_{de}	PB_{de}
NB_e	NB_u 1	NB_u 2	NS_u 3	NS_u 4	ZZ_u 5
NS_e	NB_u 6	NS_u 7	NS_u 8	ZZ_u 9	PS_u 10
ZZ_e	NS_u 11	NS_u 12	ZZ_u 13	PS_u 14	PS_u 15
PS_e	NS_u 16	ZZ_u 17	PS_u 18	PS_u 19	PB_u 20
PB_e	ZZ_u 21	PS_u 22	PS_u 23	PB_u 24	PB_u 25

The fuzzy number representing the control signal is determined from the rule table in a form of fuzzy linguistic terms. For example, if e(k) has a non-zero membership degree in the fuzzy number NB and de has a non-zero membership degree in the fuzzy number PS, then the rule number 4 is fired indicating that u has a non-zero membership degree in the fuzzy number NS. This rule (rule #4) is expressed by a linguistic term as:

***IF** e is NB **AND** de is PS **THEN** du is NS.*

This expression can also be written in a shorter form by eliminating e, de, and u.

IF NB_e **AND** PS_{de} **THEN** Ns_{du}.

This is called a rule. Multiple rules are connected to each other by the term ELSE. Therefore, the linguistic representation and cartesian products of the rule table given by Table 2 becomes as follows:

Rule 1 ⟶ IF NB_e AND NB_{de} THEN NB_u ELSE ⟶ $R1=E1 \times U1$
Rule 2 ⟶ IF NB_e AND NS_{de} THEN NB_u ELSE ⟶ $R2=E2 \times U2$
Rule 3 ⟶ IF NB_e AND ZZ_{de} THEN NS_u ELSE ⟶ $R3=E3 \times U3$

....
....

Rule 25 ⟶ IF PB_e AND PB_{de} THEN PB_u ⟶ $R25=E25 \times U25$

where $E1=NB_e \wedge NB_{de}$, $E2=NB_e \wedge Ns_{de}$, ... and so on. $U1=NB_u$, $U2=NB_u$, ..., and so on. The symbol $\wedge$ stands for intersection. Since the rules are connected to each other by the term ELSE, the overall relation matrix can be then obtained with the union of all the rules as:

$$R = R1 + R2 + R3 + \ldots\ldots + R25 = \bigcup \sum_{i=1}^{25} R_i \quad (1)$$

In fact, the table, given as the rule table, represents this relation. If a relation and one of the fuzzy sets used in that relation are known, then the other fuzzy set can be obtained by applying the compositional rule of inference. Since the relation R has a form of

$$R=E\times U \tag{2}$$

where R and E are known. U is obtained using the compositional rule of inference.

$$U=E \circ R \tag{3}$$

This result can be written in terms of membership degrees:

$$\mu(u)=\max\left[\min(\mu(e),\mu(R)\right] \tag{4}$$

is obtained. This is the membership degree of u in the fuzzy number corresponding to the related rule which is associated with the fuzzy numbers of e and de.

The final stage of the FL controller is called *defuzzifier* where the fuzzy membership degrees are converted to crisp values. Different methods are applied to convert the fuzzy numbers to crisp equivalencies. However two methods, the maximum of maxima (MOM) and the center of area (COA), are usually applied. The *center of area*, which is also called the *center of gravity method* is used in this study. The crisp value corresponding to the center of the resultant fuzzy subset areas are assigned for u when the COA method is applied. This method is formulated as in Equation (5).

$$u(k)=\frac{\sum_{i=1}^{25}\mu_i(u)\ u_i}{\sum_{i=1}^{25}\mu_i(u)} \tag{5}$$

5. VALIDATION

In order to validate the performance of the proposed FL controller, the same system is also simulated using a classical PI controller. The comparison of the resultant time responses of the door position from both controllers are shown in the next section under the same operating conditions. The details of the PI controller will not be given here since the main target of this paper is not the design of PI controllers. However, the simulation diagram of the system with PI controller is shown in Figure 5.

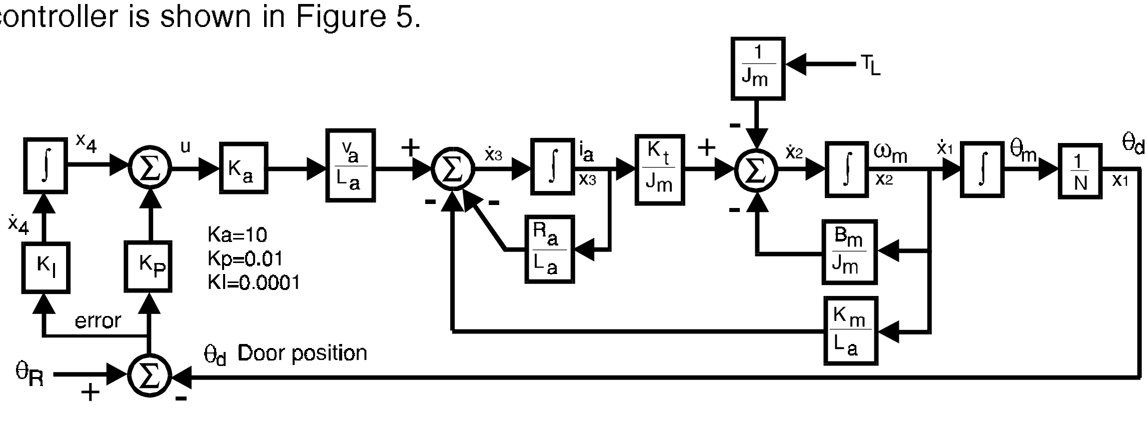


Figure 5. Simulation diagram of the system with PI controller.

6. RESULTS

Simulation results of the system studied are given in Figures 6 to 9. In all these resultant figures, the simulation was started with an initial reference door position of 40 degrees while the door is closed. Therefore, after the simulation is started, the door position varies from 0 to 40 degrees in a few seconds and remains standstill at 40 degrees until a new reference position is given. The new reference position may be given at any instant of time. However, in order to compare the results of FLC and PI controllers, the position was first reduced to from 40 to 30 degrees at t=7.5 seconds with an amount of 25% change, then it was increased to 50 degrees at t=11.25 seconds with an amount of 50% change in the position. As it can be seen from Figure 6, the resultant time responses of the door position with FLC and PI controllers are very similar, almost identical, so that the difference between these two responses were able to be seen after subtracting the response with PI controller from the response with FLC. That difference is also depicted in Figure 6.

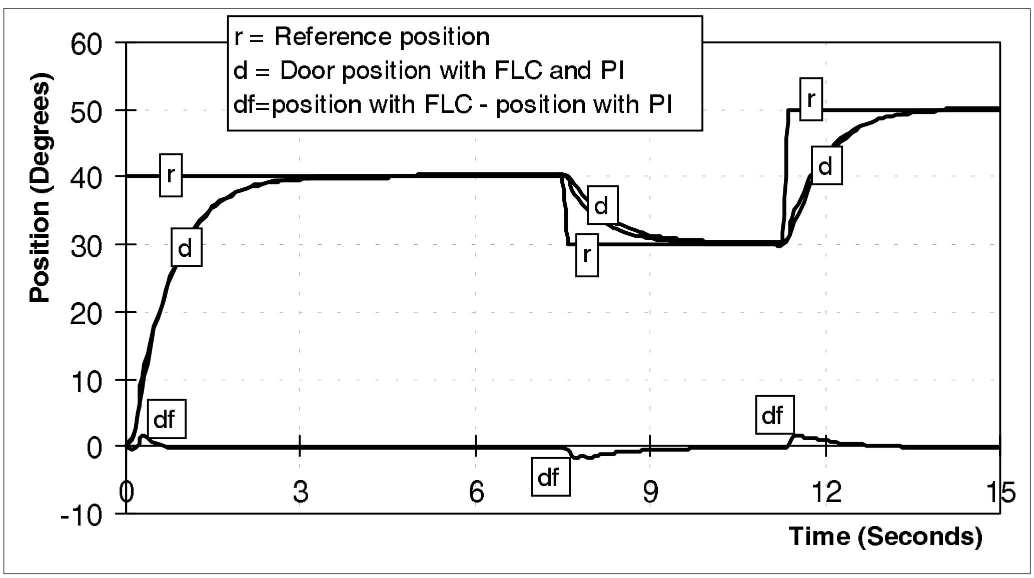


Figure 6. Time response of the door position for different reference positions.

The position error of the door with FLC is given in Figure 7, where the error is zero during steady-state operation except the transient state as it is expected.

As it was stated before, the voltage applied to the motor should be zero when the door and the reference positions are the same since it was assumed that a mechanical arrangement is used to keep the door standstill at desired position. Under these conditions, the motor speed should also be zero when the door is at desired position, i.e, not moving. Figures 8 and 9 shows that these requirements are satisfied.

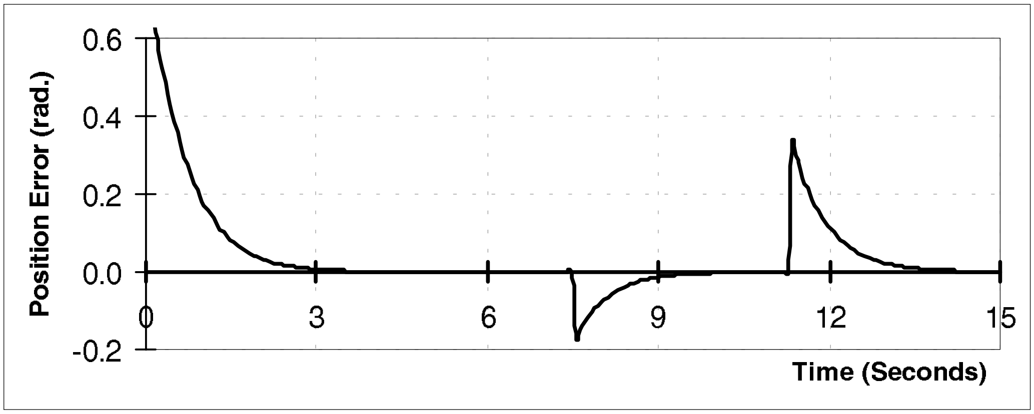


Figure 7. Variation of the position error.

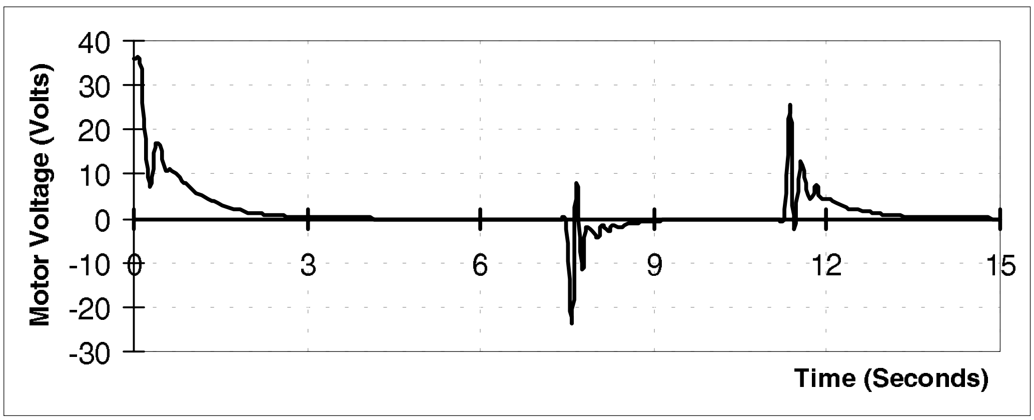


Figure 8. The voltage applied to the motor.

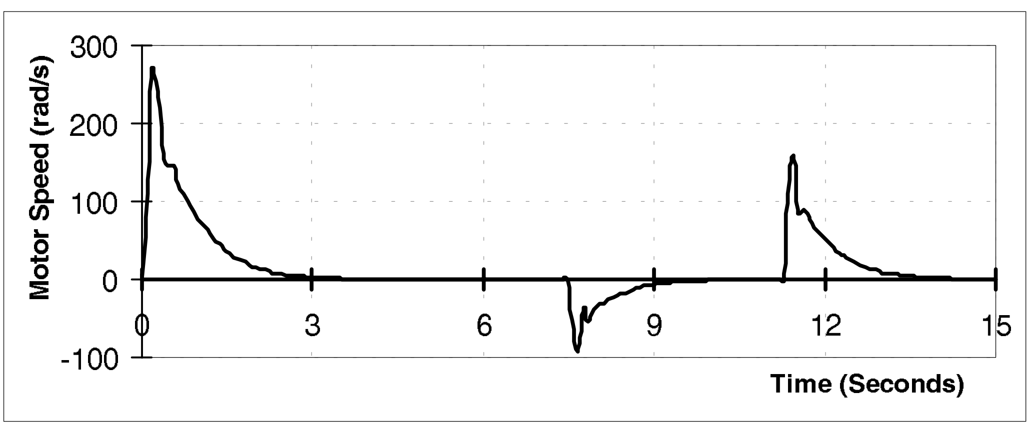


Figure 9. Variation of the motor speed.

7. CONCLUSIONS

A fuzzy logic based controller is designed and used in a position system where the reference set point varies between 0 and 90 degrees as step functions in terms of angles representing door openings. The performance of the proposed fuzzy logic controller is compared with that of a PI controller for validation, and satisfactory results are obtained. Due to a zero steady-state error, the motor driving the door operates only to move the door toward the target position. The voltage applied to the motor becomes zero causing a full stop of the motor when the position error is zero. This operating conditions are obtained by generating the control signal directly from the error signal. As it was expected, the door moves toward the target position quickly and slows down near the target for a smooth full stop.

8. REFERENCES

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9. APPENDIX

PMDC motor parameters:

R_a= resistance of armature winding =1.4 Ohm
L_a= inductance of armature winding = 0.0805 H
K_m= voltage constant = 0.095 V/rad
K_t = torque constant = 0.095 Nm/A.
J_m= moment of inertia = 0.0007432 kgm^2,
B_m= viscous constant = 0.000431 Vs/rad.
V_a= Nominal armature voltage =36 V
N= Turns ratio of the gears = 2.67