Design of a fuzzy logic proportional integral derivative controller of direct current motor speed control

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ABSTRACT

Direct current (DC) motor speed control is useful. Speed can be modified based on needs and operations. DC motors cannot control their speed. To control the DC motor's speed, a dependable controller is needed. The DC motor speed will be controlled by a fuzzy logic proportional integral derivative controller (FLC-PID). The DC motor circuit's electrical and mechanical components have been modeled mathematically. Ziegler-Nichols is used to tune the PID controller's gain parameters. The FLC controller employs 3×3 membership function rules in conjunction with the MATLAB/Fuzzy Simulink toolbox. Real hardware was attached to the simulation to evaluate the DC motor speed control using the fuzzy logic PID controller. DC motors with FLC PID controllers, FLC controllers, and DC motors alone will be compared for the transient response. The DC motor with an FLC PID controller performed better in this study.

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1. INTRODUCTION

Nowadays, most electrical equipment uses electric motors to run, such as machines, household appliances, and electric cars, and it is responsible for most of the mechanical growth that we can see around us. An electric motor is an electrical machine that converts electrical energy into mechanical energy. There are three categories of motors, which are alternating current (AC) motors, brushed direct current (DC) motors, and special-purpose motors for example the stepper motor, universal motor, reluctance motor, and others [1]. DC motors are employed in a number of control systems, including the one already stated and process control [2]. For several purposes, DC motors are frequently chosen over AC motors.

DC motors feature a wide range of speed control choices, including both below and above the rated speed, making them perfect for low-torque applications [3]. Besides, DC motors also has a large and powerful starting torque, has a more affordable price, requires simple maintenance, and takes little or even no time for maintaining [4]. DC motors have been used in many applications such as conveyors and turntables, and also other systems that are required for variable speed and constant or low-speed torque or accuracy in the position [5].

Furthermore, to make sure the motor running it is necessary to control the speed it refers to the actual speed as feedback. To control the speed of the DC motor, a few ways can be used such as using a controller. There will be two categories of control from linear control which are proportional control and the other one is proportional-integral-derivative (PID) control. Usually, in the application, the PID controller is popular to be used due to its three-term functionality which can accommodate both transient and steady-state responses [6], [7].

However, the PID controller only does not give adequate outcomes [8]. Here, the fuzzy logic controller will provide some way out as it will be combined with the PID controller. Combining the fuzzy and PID controllers, with the fuzzy controller's purpose being to tune the PID controller parameters based on the error and change of error, could be a useful alternative to traditional PID control [9], [10]. A fuzzy logic controller (FLC) developed by Zadeh [11] has been used in process control and successfully employed to cope with ambiguous and ill-defined situations [12]–[15]. FLC is a knowledge-based controller (KBC) with the ability to more effectively control the process [13], [16]. Fuzzy logic helps in checking nonlinear frameworks and has proven to be effective, particularly in the case of issues that are hard to handle mathematically [17], [18]. Subsequently, the fuzzy logic theory is currently utilized as an option in contrast to the programmed control frameworks.

A fuzzy controller is strong concerning dynamic change and extensive stability range. Even for indefinite nonlinear systems, the theory of fuzzy control grants a nonlinear controller the ability to execute an intricate nonlinear control action [6], [11]. Fuzzy control theory has been demonstrated successful in various applications changing from quick cycles of motion control such as advanced mechanics, modified pendulums, and others to somewhat more slow frameworks for heat trade, machine computerization, and camera focus. Fuzzy logic controllers have four parts which are fuzzification, rule base, inference engine, and defuzzification interface [19].

The exceptional component of fuzzy logic techniques is in copying human experience and instinct in managing inconclusiveness [20], [21]. This element works on the adaptiveness capacity of closed-loop frameworks such that modeling uncertainties are tolerated without much loss in performance [21]. A fuzzy logic controller just depends on inexact and linguistic data [8]. The resemblance of articles to ambiguous properties can be portrayed by the fuzzy membership function. The data shown by a fuzzy set such as fuzzification, defuzzification, and others are included within the membership function. Fuzzification transforms input data into linguistically appropriate values [9].

Fuzzification is the way of changing a crisp quantity to a fuzzy quantity [22] where fuzzification includes the method involved with changing the crisp input to a fuzzy value based on the data in the information base. This can be accomplished by recognizing the different known crisp and deterministic quantities as totally un-deterministic and very unsure [23]. Meanwhile, defuzzification is a reversal of fuzzification. If the mapping of fuzzification is done to change over the crisp outcomes to fuzzy outcomes, a defuzzification mapping is done to change over fuzzy outcomes into crisp outcomes [24]. This procedure is equipped for creating a non-fuzzy control activity that delineates the possible distribution of a derived fuzzy control activity. A fuzzy logic-proportional integral derivative (FLPID) controller is utilized to perform this experiment to adjust the speed of the DC motor.

Fuzzy PID controllers have been used in industry, especially for complicated and unclear model systems. The fuzzy PID control is a better method of regulating because it can provide easy and effective control, plays fuzzy control robustness, has good dynamic response and rising time as well as overstrike features [25]. The FLPID controller is unaffected by changes in the system's structure, parameters, or operating points [26]. Furthermore, it is simple to implement in real-world systems.

The fuzzy PID controller has its unique features which are it has the same linear structure as the traditional PID controller, but with constant coefficient, and self-tuned control gains. In addition, the special characteristic of this proposed controller is it is based on the traditional discrete PID controller, which is used to construct the fuzzy control law. Then, simple triangle membership functions with only four fuzzy logic "if-then" rules are used. The phases of fuzzification, control-rule execution, and defuzzification are all incorporated into the fuzzy control law's final formulation. Due to the resulting control, the law is an explicit conventional formula, the controller functions similarly to a traditional PID controller and the fuzzification-rules defuzzification technique is not required during the control process [27].

Carvajal *et al.* [28] designed and implemented the fuzzy PID controller to control some well-known nonlinear systems that defy the linear PID controller's common assumptions such as robotic manipulators. By referring to the derivation that has been made in this study for the fuzzy PID controller, it is strongly shown that the proposed controller provides better performance compared to the conventional PID controller. It has been mentioned that this type of controller manages to endure a large number of poor controller gain selections or implementations, which would make most traditional controllers unstable.

The fuzzy PID controller has been applied to search for optimal values for the PID controller parameters by implementing the proposed controller-based load frequency control (LFC) in a multi-area interconnected power system [29]. Different disruptions in area-1, area-2, and area-3 are simulated in the integrated multi-area power system. Also, the effect of the LFC control approach on step load disturbance-induced fluctuations is investigated. The new method is compared to the traditional Ziegler-Nichols (Z-N) method as well as the heuristic particle swarm optimization (PSO) method. At the end of this research, it is obvious that with the suitable PID parameters, system frequency and tie-line power flow variations are effectively suppressed. The results are compared to those obtained using the heuristic PSO approach and the conventional Z-N method. The proposed approach was shown to be the most efficient in the comparison analysis.

Other than that, the fuzzy PID controller has been enforced also for controlling the speed of the DC motor. In this experiment, the controller's parameters are modified based on fuzzy logic. As for the fuzzy logic controller, it has two inputs where the first is the difference in motor speed between the reference and actual speed while the second is the speed change error. Then, the output of the FLC which is the PID controller's parameters is utilized in controlling the DC motor's speed. Bansal and Narvey [30] made a comparison between the traditional PID controller on a DC motor with the proposed method, a self-tune PID controller using fuzzy logic in the aspects of transient and steady-state response.

At the end of the study based on the simulation that has been done in MATLAB/Simulink software, the authors concluded that the self-tuning PID controller outperforms the conventional PID controller in both aspects that have been mentioned earlier. When compared to the traditional PID controller, self-tuning FLC has a better dynamic response curve, shorter time response, small overshoot, small steady-state error, and high steady precision. From a few literature reviews that have been done, the fuzzy PID controller shows a better performance especially when it is being compared with the conventional PID controller.

The main purpose of this paper is to examine the performance of the DC motor for speed control purposes by implementing a controller that is a fuzzy logic PID controller where the parameters were tuned by using the Ziegler-Nichols method. Then, to justify the performance of the DC motor speed control with the fuzzy logic PID controller that has been done in simulation, a real experiment was done by interfacing the real hardware with the simulation part. The performance of the DC motor with FLC PID controller, DC motor with FLC controller, and DC motor only will be compared in terms of the transient response aspects.

2. METHOD

This research focused on designing the fuzzy logic PID controller via simulation in MATLAB/Simulink and the real experiment with hardware. The value of the DC motor parameters used is listed in Table 1. Figure 1 shows the model of the DC motor that has been designed in Simulink.

Table 1. DC motor parameters

Parameter	Nomenclature	Value
Armature resistance	R	0.5 Ω
Armature inductance	L	0.02 H
Damping friction of the mechanical system	K	0 Nm
Back electromotive force constant	K_b	1.25 Nm/A
Moment of inertia	J	0.1 kgm^2

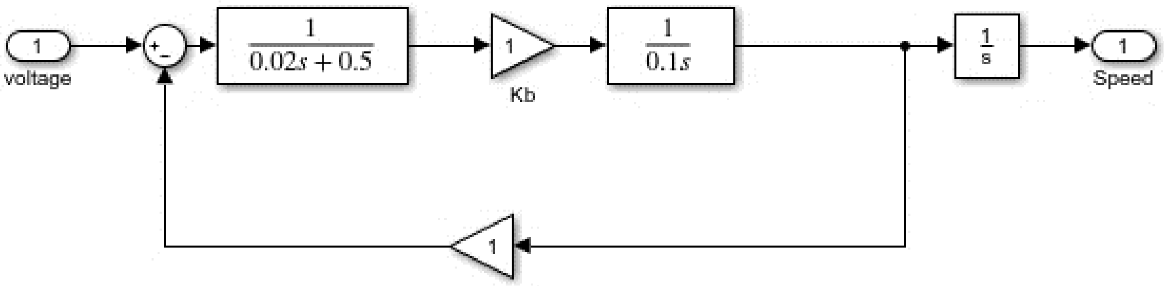

Figure 1. DC motor modeling

MATLAB/Simulink has been used to develop the PID controller modeling system. Several gain factors have been evaluated to achieve the optimal gain value for the proposed controller gain which are proportional gain, K_p, integral gain, K_i, and derivative gain, K_d. The best configuration of gains value is once it will operate the program with minimal overshooting, less steady-state failure including low steady-state time [8]. The parameter of the PID controller has been obtained as shown in Table 2. Figure 2 shows the modeling of the PID controller for the DC motor.

Table 2. PID controller parameter value

Controller	Gain's value		
	K_p	K_i	K_d
PID	1.795	23.16	0.0239

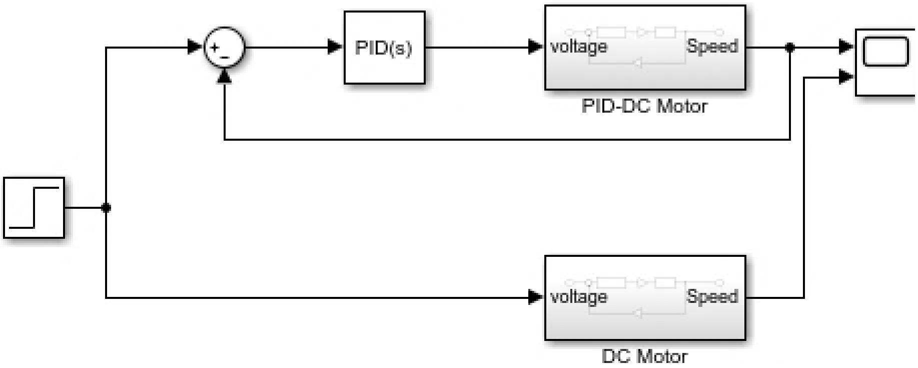

Figure 2. PID controller modeling for DC motor

In this experiment, a fuzzy logic controller 3×3 matrix control rule has been designed. Fuzzification will be the first stage in the process of the fuzzy logic controller. This method turns controller inputs into information that can be easily used by the inference mechanism for activating and implementing rules. By this phase, the values of crisp inputs are fully changed to the values of fuzzy inputs [31]. The input for this fuzzy logic controller is voltage. Meanwhile, the output variable for this fuzzy logic controller is speed. Table 3 shows the detailed parameter for the input voltage of the membership function. Meanwhile, the output speed of the membership function is shown in Table 4.

Table 3. Input voltage of membership function

Input: Voltage	
Low	0 to 6
Medium	6 (No change)
High	6 to 12

Table 4. Output speed of membership function

Output: Speed	
Slow	0 to 75
Normal	75 to 150
Fast	150 to 225

Furthermore, Figure 3 shows the hardware connection that has been developed for this experiment and Figure 4 shows the modeling system of the fuzzy logic-PID controller for the DC motor. The fuzzy logic-PID controller modeling for the DC motor has been designed in the MATLAB/Simulink software and will be simulated and interfaced with the hardware to get the output value of this experiment. In this experiment, three conditions have been used which are if the input voltage is low, the output fuzzy speed will be slow, the second condition is if the input voltage is medium, the output fuzzy speed will be normal and the last one is if the input voltage is high, the output fuzzy speed will be fast.

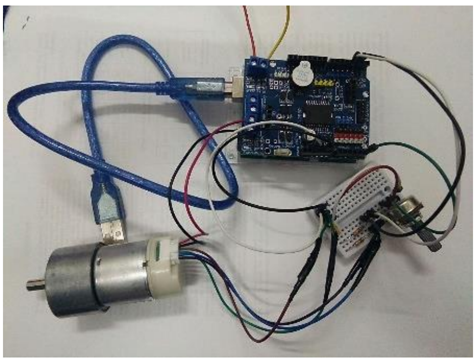

Figure 4. Hardware circuit connection for the experiment

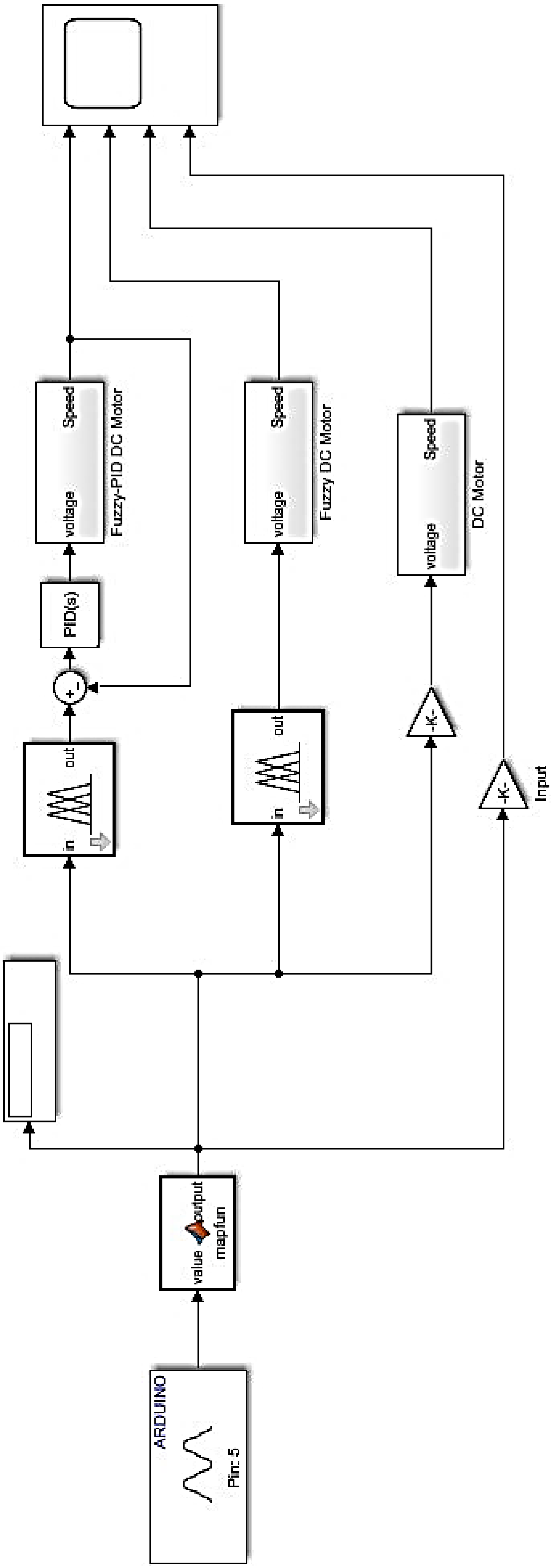

Figure 3. Simulation circuit for the experiment

3. RESULTS AND DISCUSSION

These results are obtained from the simulation that had been done using MATLAB/Simulink software. It is divided into three parts of results which are the result of a DC motor without a controller (DC motor), the results of a DC motor with the fuzzy controller as well as the result of a DC motor with a fuzzy PID controller (fuzzy PID DC motor). For this experiment, three different cases of results with various values of voltage input have been obtained which are 4, 8, and 12 V.

3.1. 4 V of input voltage

The input voltage has been set to 4 V by using the potentiometer. Figure 5 shows the output graph of the circuit in Simulink software and hardware after being run. The setpoint input value is 106 rpm when the input voltage is 4 V. The result for three systems when the input voltage is 4 has been shown in Table 5.

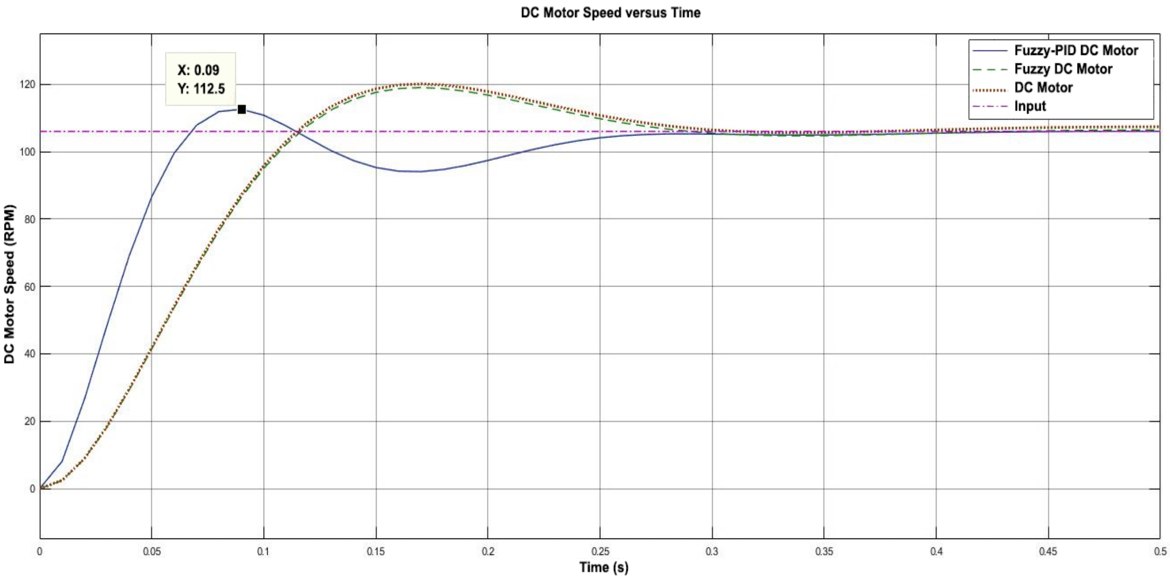

Figure 5. Output graph of the experiment with 4 V of voltage input

Table 5 shows that by implementing the fuzzy PID controller at the DC motor, the value of rising time T_r can be decreased compared to a fuzzy DC motor and a DC motor without a controller. The percentage of the rise time decreased by 42.11% for the fuzzy PID DC motor compared to the fuzzy DC motor meanwhile it is reduced by 43.59% when compared to the DC motor without any controller. With a percentage difference of 25.97% for the settling time characteristic, the DC motor with a fuzzy PID controller has been reduced compared to a fuzzy DC motor only and 26.19% compared to a DC motor without a controller.

Table 5. Transient response for DC motor, fuzzy logic DC motor, and fuzzy logic PID DC motor

Type of controllers	Transient response			
	Rise time, T_r (s)	Settling time, T_s (s)	Peak time, T_p (s)	Overshoot, %
Fuzzy logic PID DC motor	0.044	0.248	0.090	112.5
Fuzzy logic DC motor	0.076	0.335	0.170	119.0
DC motor	0.078	0.336	0.170	120.1
Percentage difference of performance of fuzzy PID DC motor compared to fuzzy DC motor (%)	42.11	25.97	47.06	5.46
Percentage difference of performance of fuzzy PID DC motor compared to DC motor (%)	43.59	26.19	47.06	6.33

For peak time, the percentage difference in the performance of fuzzy PID controller DC motor compared to both fuzzy DC motor and DC motor without a controller is the same where it has decreased by 47.06%. Besides, the overshoot value of a DC motor with a fuzzy PID controller is also less by 5.46% than the overshoot value of a DC motor with a fuzzy controller only and compared to a DC motor without a controller is reduced up to 6.33%.

3.2. 8 V of input voltage

The input voltage has been set to 8 V by using the potentiometer. Figure 6 shows the graph output of the circuit in Simulink and the hardware after being run. The setpoint input value is 117.7 rpm when the input voltage is 8 V. The result for three systems when the input voltage is 8 has been shown in Table 6.

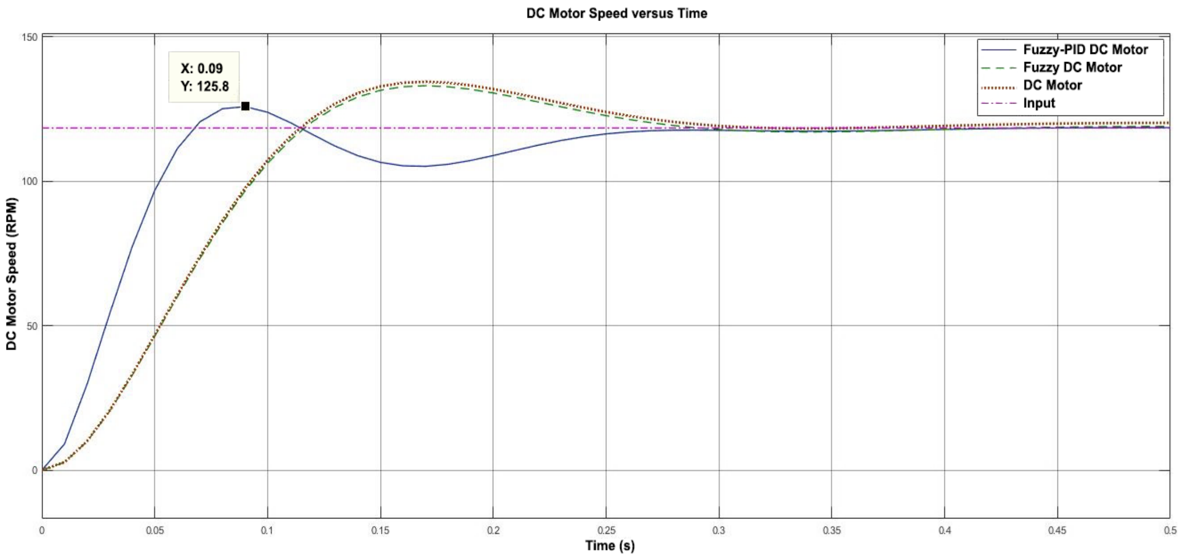

Figure 6. Output graph of the experiment with 8 V of voltage input

Table 6. Transient response for DC motor, fuzzy logic DC motor, and fuzzy logic PID DC motor

Type of controller	Transient response			
	Rise time, T_r (s)	Settling time, T_s (s)	Peak time, T_p (s)	Overshoot, %
Fuzzy PID DC motor	0.045	0.240	0.090	125.8
Fuzzy DC motor	0.077	0.348	0.170	133.0
DC motor	0.078	0.350	0.170	134.4
Percentage difference of performance of fuzzy PID DC motor compared to fuzzy DC motor (%)	41.56	31.03	47.06	5.41
Percentage difference of performance of fuzzy PID DC motor compared to DC motor (%)	42.31	31.43	47.06	6.4

Table 6 shows that using a fuzzy PID controller at the DC motor can lessen the value of rising time compared to a fuzzy DC motor and DC motor without a controller. The percentage of the rise time decreased by 41.56% for the fuzzy PID DC motor compared to the fuzzy DC motor meanwhile it is reduced by 42.31% when compared to the DC motor without any controller. With a percentage difference of 31.03%, a DC motor with a fuzzy PID controller has been reduced compared to the settling time value of a fuzzy DC motor only and 31.43% compared to a DC motor without a controller.

For peak time, the percentage difference in the performance of fuzzy PID DC motor compared to both fuzzy DC motor and DC motor without a controller is the same where it has decreased by 47.06%. Besides, the overshoot value of a DC motor with a fuzzy PID controller is also less by 5.41% than the overshoot value of a DC motor with a fuzzy controller only and compared to a DC motor without a controller is reduced up to 6.4%.

3.3. 12 V of input voltage

The input voltage has been set to 12 V by using the potentiometer. Figure 7 shows the output graph of the circuit in Simulink and the hardware after being run. The setpoint input value is 186.5 rpm when the input voltage is 12 V. The result for three systems when the input voltage is 12 has been shown in Table 7.

Table 7 shows that using a fuzzy PID controller at the DC motor decreases the value of rising time compared to a fuzzy DC motor and DC motor without a controller. The percentage of the rise time decreased by 42.31% for the fuzzy PID DC motor compared to the fuzzy DC motor meanwhile it is reduced by 43.75% when compared to the DC motor without any controller. With a percentage difference of 31.81%, a DC motor with a fuzzy PID controller has been reduced compared to the settling time value of a fuzzy DC motor only and 32.19% compared to a DC motor without a controller.

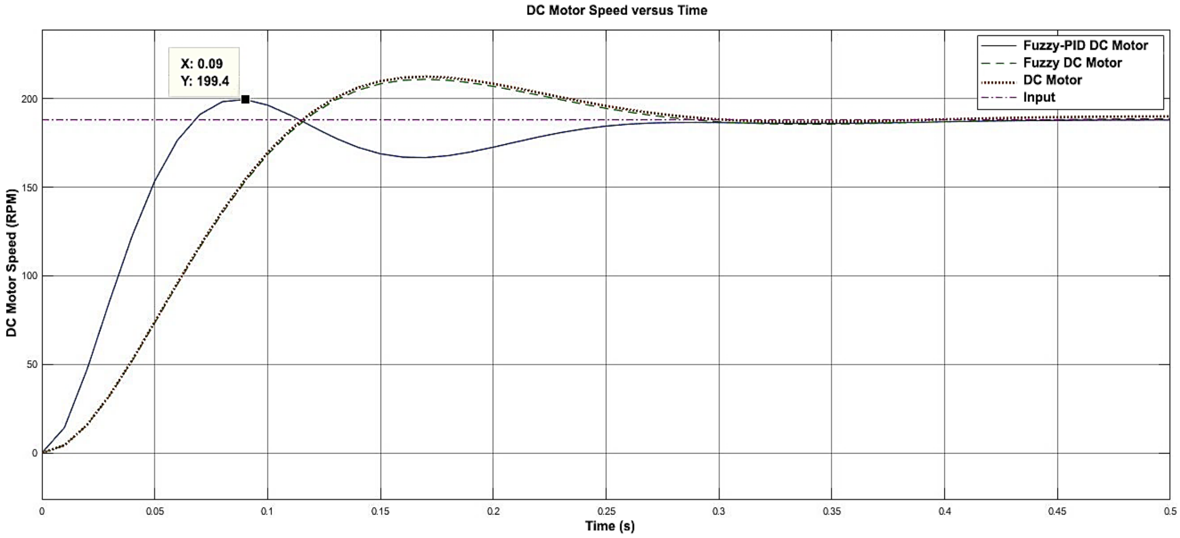

Figure 7. Output graph of the experiment with 12 V of voltage input

Table 7. Transient response for DC motor, fuzzy logic DC motor, and fuzzy logic PID DC motor

Type of controllers	Transient response			
	Rise time, T_r (s)	Settling time, T_s (s)	Peak time, T_p (s)	Overshoot, %
Fuzzy PID DC motor	0.045	0.238	0.090	199.4
Fuzzy DC motor	0.078	0.349	0.170	210.9
DC motor	0.080	0.351	0.170	212.4
Percentage difference of performance of fuzzy PID DC motor compared to fuzzy DC motor (%)	42.31	31.81	47.06	5.45
Percentage difference of performance of fuzzy PID DC motor compared to DC motor (%)	43.75	32.19	47.06	6.12

For peak time, the percentage difference in performance of fuzzy PID DC motor compared to both fuzzy DC motor and DC motor without a controller is the same where it has decreased by 47.06%. Besides, the overshoot value of a DC motor with a fuzzy PID controller is also less by 5.45% than the overshoot value of a DC motor with a fuzzy controller only and compared to a DC motor without a controller is reduced up to 6.12%.

4. CONCLUSION

In this study, the FLC-PID controller was successfully developed by using MATLAB/Simulink software. The hardware that has been designed had successfully interfaced with the simulation in the software with different conditions of the DC motor which are DC motor with FLC-PID controller, DC motor with FLC controller, and DC motor without any controller to produce the speed of the DC motor. Based on the experimental result, the DC motor with an FLC-PID controller provides better performances in terms of the transient response characteristics with different values of voltage input compared to other conditions of the DC motor. Three different values of input voltage have been implemented in this research 4 V, 8 V, and 12 V. Output responses for each of the input voltages have been recorded and it can be seen that for different values of voltage input, the response is better when the proposed controller is being used in the system.

It can be proved by referring to each of the terms in the transient response for all three input voltages used where the rising time required by the DC motor with the proposed controller for this system is lower in value compared to the DC motor with the FLC controller and the DC motor without using any controller which is 0.044 s, 0.045 s and 0.045 s for three different input voltages. For the settling time, the DC motor with the FLC-PID controller comes out with 0.248 s, 0.240 s, and 0.238 s for 4 V, 8 V, and 12 V subsequently. As for the peak time, all three input voltages have the same value which is 0.090 s and the last characteristic is the percentage overshoot which takes 112.5%, 125.8%, and 199.4% for each input voltage.

Therefore, it can be concluded that applying the FLC-PID controllers will produce an outperforming performance for the DC motor speed compared to the DC motor with an FLC controller only and the DC motor without any controller. In this study, some improvements can be done such as by tuning the controller's parameter using the latest tuning technique, for example, the swarm intelligence algorithm where the parameters obtained are more accurate and precise. The last one is implementing a lower value of integral gain. This is because a higher value of integral gain can cause an overshoot to the system which will affect the peak time.

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