COMPARATIVE ANALYSIS OF SPEED CONTROL OF DC MOTOR USING FUZZY LOGIC CONTROLLER AND PID CONTROLLER

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ABSTRACT

The idea of the speed control system is to maintain the speed of direct current (DC) motor at a desired value under varying conditions such as motor load variation, disturbances, non-linearity, etc. Attempts have been made with many methodologies to provide control mechanisms for achieving precision and improving quality of production. In this paper, a mathematical model of a dc motor is presented without controller. A proportionalintegral derivative (PID) is designed to control the speed of the sample motor. The Zeigler-Nichols tuning method was adopted to tune the PID controller to achieve optimal performance. A fuzzy logic controller (FLC) was also designed to control the motor. Appropriate linguistic variables and membership functions were chosen for the fuzzy logic control implementation. A comparative analysis of the performance indices of the controllers such as rise time, settling time, maximum overshoot, and peak speed value showed that the FLC performed better than the PID controller on the DC motor. Also, both controllers produced better results than the motor without a controller. All the modeling and simulation were carried out in MATLAB/ SIMULINK environment.

Key Words: DC motor, MATLAB/SIMULINK, PID controller, Fuzzy logic controller

I INTRODUCTION

DC motor speed is a very important variable in manufacturing and industrial processes. The idea of the speed control system is to maintain the desired speed of the DC motor at various conditions such as changes in motor load demand, disturbances, etc. Attempts have been made to provide control mechanisms for the purposes of achieving precision and improving or attaining desirable quality of production. These existing control mechanisms include proportional (P), proportionalintegral (PI), proportionalderivative (PD), proportionalintegral derivative (PID), optimal, lead – lag, adaptive, fuzzy logic (FLC), neural networks (NNCs) etc. The first four approaches have been used to achieve improved performance of DC motors.

Among the four approaches, PID have been used in industrial control processes due to its robustness and improved performance in a wide range of operating conditions when compared with P, PI and PD controllers. However, PID controllers perform poorly when applied to DC motor control due to certain motor constraints listed below.

The presence of non- linearity in DC motors such as saturation and friction, time-varying nature of motor parameters under operating conditions and existence of noise in system loop. To improve on the performance of a PID controller. One of such methods is to use a fuzzy logic controller (FLC) instead of a PID controller. In this paper FLC is used which is a relatively new approach and is expected to have potentials of accomplishing the task of PID controllers with better precision.

II MATHEMATICAL MODELING OF MAGNET DC MOTOR

The system chosen is an armature controlled separately excited permanent magnet DC

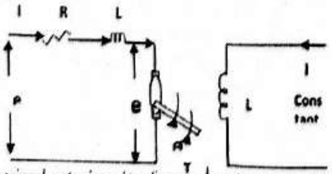

Fig 1: Equivalent circuit of separately excited D.C. motor.

where I_f is field current, L_f is field inductance, R_a is whereas the resistance of the armature winding and its inductance is L_a. In the description of the motor, the armature reaction effects are ignored. This assumption is justifiable since the motor used has either interpoles or compensating winding to minimize the effects of armature reaction. In armature-controlled scheme.

The field current is kept constant, as a result. the flux induced by the field winding remains constant, and usually it is held at its rated value Φ. e_b is the back emf in volts. In a separately-excited DC motor, the back emf is proportional to the product of speed of motor and the constant field. Considering the armature-controlled D.C. motor in figure 1 and assuming that the demagnetizing effect of armature reaction is neglected, the magnetic circuit is assumed linear and the field voltage is constant i.e. I_f is constant.

The back EMF e_b is directly proportional to the speed, hence:

$$e_b(t) = k_b \, {}^{d\theta}/_{dt} = k_v\omega(t) \qquad (1)$$

Applying KVL to the armature circuit we get

$$e_a(t) = R_a i_a(t) + L_a\frac{di_a}{dt} + e_b(t)$$

From Newton's law, the motor torque was obtained as motor (PMDC). Its equivalent circuit is shown in figure 1.

$$T(t) = J\frac{d^2\theta(t)}{dt^2} + B\frac{d\theta(t)}{dt} + \tau_L(t)$$

Where $\tau_L(t)$ is the motor load torque (Nm)

Taking Laplace transform, the above equations were formulated as $E_b(s) = K_v\Omega(s)$ (4)

$$E_a(s) = (R_a + L_a s)I_a(s) + E_b(s) \quad (5)$$

$$T_m(s) = (Js + B)\Omega(s) + T_L(s) = K_T I_a(s) \quad (6)$$

All variables above are at zero initial conditions

The angular position is given as

$$\theta(s) = \frac{1}{s}\Omega(s) \quad (7)$$

The above equations can be represented in block diagram form as shown in figure 2

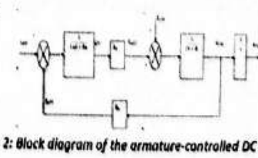

Fig 2: Block diagram of the armature-controlled DC motor.

The transfer function with respect to input voltage is expressed as: $G(s) = \frac{\Omega(s)}{E_a(s)} = \frac{K_T}{(L_a B + R_a J)s + R_a B + K_v K_T}$ (8)

$$G(s) = \frac{K_T}{[L_a J s^2 + (L_a B + R_a J)s + (R_a B + K_v K_T)]} \quad (9)$$

The specified DC motor parameters is given in table I (Ahmed *et al.*, 2013).

Table I: PMDC motor technical data

Parameters	Values	Units
Rated Power (P)	3.7	KW
Terminal voltage (Va)	48	V
Speed (Nm)	1750	RPM
Torque Constant (Kt)	1.28	N-m/A
Back EMF constant(Kv)	0.0045	V/(rad/sec)
Inertia (J)	0.02215	kg.m2
Armature Inductance (La)	0.1214	H
Armature Resistance (Ra)	11.4	Ω
Motor Viscous Coefficient (B)	0.002953	Nm/(rad/sec)

Putting these parameter's values into the transfer function in (9), the equation becomes:
is further simplified as

$$G(s) = \frac{128}{[0.2689s^2 + 0.2529s + 3.9424]} \quad (10)$$

Equation (10) represents the transfer function of the DC motor based on chosen motor parameters. The DC motor model developed in simulink environment in continuous-time domain is simulated to obtain the behaviour of the motor. In Simulink, the DC motor model is represented as seen in figure 3. The input to the model is the supplied dc voltage which drives the electrical field circuit of the motor, while the output is specifically the rotational speed of the motor shaft. It is important at this point to assess the performance and the stability of the PMDC motor before commencing the simulation.

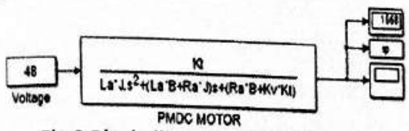

Fig 3 Block diagram of PMDC motor

(III) MODELLING OF PERMANENT MAGNET DC MOTOR WITH PID

The general transfer function model for a PID controller is shown in equation 11 below with a pre-filter in the controller structure to filter the derivative action of the PID.

$$\frac{\omega(s)}{e(s)} = K_p\left(1 + \frac{1}{K_i s} + \frac{sK_d}{1 + s\frac{K_d}{N}}\right) \quad (11)$$

This section shall focus on the design of the Proportional Integral Derivative (PID) controller. A closed loop Proportional Integral Derivative controller was designed and adopted for the purpose of controlling the speed of the designed DC motor system. The design of the PID controller following the block diagram of the PID controller system shown in figure 4, the relationship between the input error e(t) and output u(t) can be formulated as follows; In Laplace domain (12) becomes

$$u(t) = K_p e(t) + K_I \int_0^t e(t) + K_D \frac{de(t)}{dt} \quad (12)$$

$$U(s) = [K_p + \frac{K_I}{s} + K_D s]E(s) \quad (13)$$

$$C(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_I}{s} + K_D s \quad (14)$$

The transfer function is expressed as

$$G(s) = \frac{(K_D s^2 + K_p s + K_I)K_T}{L_a J s^3 + (R_a J + BL_a + K_D)s^2 + (R_a B + K_e K_T + K_p)s + K_I K_T} \quad (15)$$

The closed loop transfer function of the above system is expressed as follows:

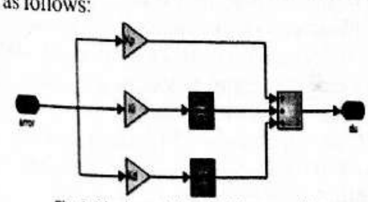

Fig 4: Block model of the PID controller

PID Tuning Parameters

The PID tuning is done using soft tuning compared with Zeigler Nichols tuning method and implemented with Simulink/Matlab. The Zeigler Nichols tuning was done by setting K_I and K_D to zero while varying K_p till a sustained oscillation is obtained. The tuned parameters were obtained using Zeigler Nichols as summarized in table II.

Table II : Zeigler-Nichols Tuning Rules.

Controller	KP	KI	KD
P	0.5Ku		
PI	0.45Ku	$1.2\,K_p/T_u$	
PID	0.6Ku	$2\,K_p/T_u$	$K_pT_u/8$

Where ultimate gain (K_u) is 2.9 and ultimate period (T_u) is 1.64 and the computed PID parameters are: K_p = 1.74; K_I = 2.122; K_D = 0.357. Next, the Cohen-Coon method is employed. Using equation (13), the gains of the PID controller were tuned to these gain values used to obtain the final transfer function model for the Cohen-Coon tuned PID controller as illustrated in table III. Table III: Tuned PID controller gains

PID Gains	Values
Proportional Gain	2.86
Integral Gain	0.35
Derivative Gain	-0.0565
Pre-filter Coefficient	50.54

$$\frac{e(s)}{E_b(s)} = \frac{2.801s^2 + 3.205s17.56}{s^2 + 50.54s} \quad (16)$$

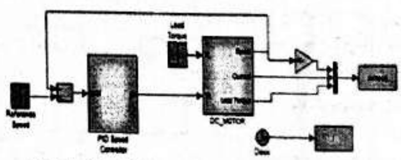

Fig 5: Simulink model of the PID controlled DC motor

(IV) DEVELOPING THE FUZZY LOGIC CONTROLLER

The designed Simulink fuzzy controller system block for the DC motor is shown in figure 6. The three principal elements in the fuzzy logic controller are; the fuzzification module (fuzzifier), the rule base and inference engine, and the defuzzification module (defuzzifier).

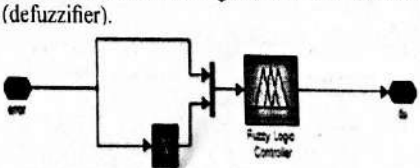

Fig 6: Fuzzy logic controller subsystem block

In building the fuzzy logic controller system, the input parameters supplied to the fuzzy controller, are unit step inputs representing reference speed error and change in error. The Mamdani algorithm is used for the implementation of the inference mechanism. A triangular membership function is defined for each linguistic variables which are; speed error (e), change in speed error (ce) and control output (u). The membership functions of the inputs and outputs are designed after the rule data base, and the controller is tested on the system to adjust any seemingly wrong parameters.

Fuzzy logic controller inputs and output linguistic variables are partitioned into seven (7) fuzzy subsets and are presented by seven (7) membership functions which are: Large Negative (LN), Medium Negative (MN), Small Negative (SN), Zero (Z), Small Positive (SP), Medium Positive (MP), Large Positive (LP). The rule base was designed based on these seven variables with the minimum inference rule. The general rules for the DC motor speed control are that if motor speed is less than the desired speed, then increase motor speed and if motor speed is more than reference speed, then reduce the speed. If the error is large positive and the change in error is large negative, then the output of the controller must be zero and there is no need to increase the motor speed to meet the reference point which is directly proportional to the voltage of the controller These fuzzy rules are summarized in the fuzzy rule matrix table IV.

Table IV : Fuzzy Rule Matrix Table

E \ Ce	LN	MN	SN	Z	SP	MP	LP
LN	LN	LN	LN	LN	MN	SN	Z
MN	LN	LN	LN	MN	SN	Z	SP
SN	LN	LN	MN	SN	Z	SP	MP
Z	LN	MN	SN	Z	SP	MP	LP
SP	MN	SN	Z	SP	MP	LP	LP
MP	SN	Z	SP	MP	LP	LP	LP
LP	Z	SP	MP	LP	LP	LP	LP

The implementation of the FLC requires the choice of four key factors which are; the number of fuzzy sets that constitute linguistic variables, mapping the measurements into the sub sets, control protocol that determines the controller behaviour and the shape of the membership functions. The fuzzy inference system editor is shown in figure 7. The blocks to the left are the inputs e(t) and ce(t). In the centre is the DC Motor's Mamdani type fuzzy inference system, and to the right is the system output u(t) where defuzzification is method used is centroid method.

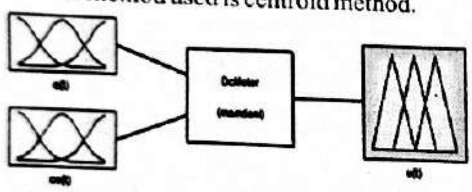

Fig 7: The fuzzy Inference System Editor

Numerical range of values for the input error and its corresponding linguistic notation ranging between -1 and 1 with seven triangular shaped membership functions.

The seven triangular shaped membership functions for the input variable error e(t) are illustrated in figure 8. Which is the same with that of for Change in error ce (t).

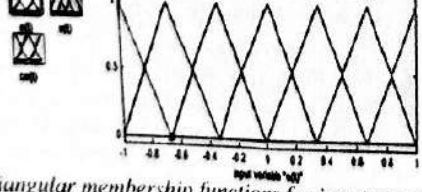

Fig 8: Triangular membership functions for input speed error e(t)

From figure 9 shows the Triangular membership functions for variable output u(t).

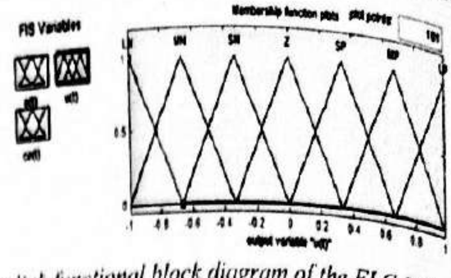

Fig 9 Simulink functional block diagram of the FLC DC motor system

The FLC set of 49 rules was created for the three linguistic variables error e(t), change in error ce(t) and the output u(t) using the minimum inference rule. Figure 10 shows the rules viewer for the fuzzy controller. The rules behaviour can be checked here by changing the error e(t), and changing the change in error ce(t) and monitoring the output u(t).

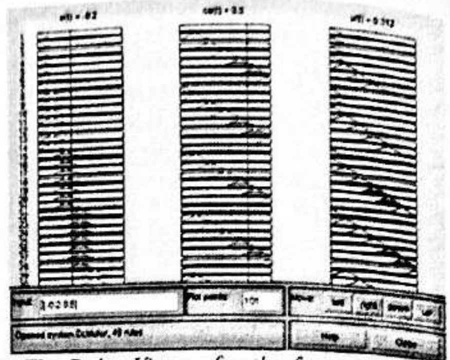

Fig10: The Rules Viewer for the fuzzy logic controller

The surface viewer shown above in figure 11 indicates that the motor speed can reach the reference point and operate smoothly. The simulation of the above block is clocked and sent to the workspace to be called up for representation in the Graphical User Interface (GUI) screen.

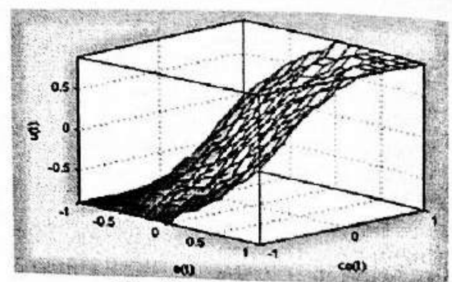

Fig 11 Surface Viewer

Figure 5 and 6, PID controller and the Fuzzy logic controller (FLC) for the DC motor system built in Simulink are simulated. The reference speed is a unit step block and the speed range is between 1 – 1750 rpm. The load torque is also a step functional block ranged between no load to 20Nm torque load.

(V) SIMULATION RESULTS AND DISCUSSIONS

(a) Open loop speed response of motor

The motor rated speed as shown in figure 12 is 1750rpm but the model was able to produce a maximum of 1558rpm with an input voltage of 48V DC. This shows the level of fidelity of the model. In order to achieve the rated speed, there is need to vary the parameters of the system and simulate several times to obtain the required result. This will be possible only if the system is redesigned and this always comes with an added cost and time. On the other hand, for best practice, there is a possibility of introducing a PID controller into the closed-loop circuit of the motor to boost the speed the required and rated value.

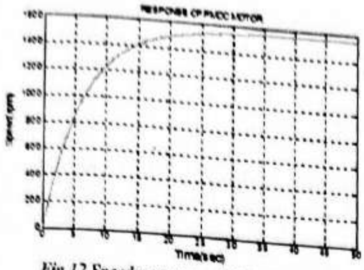

Fig 12 Speed response of PMDC motor

(b) closed loop system Performance for Reference Speed of 1200 rpm on no - load

The system response and performance for a reference speed of 1200 rpm without control, with PID control and with FL control at no load, are presented.

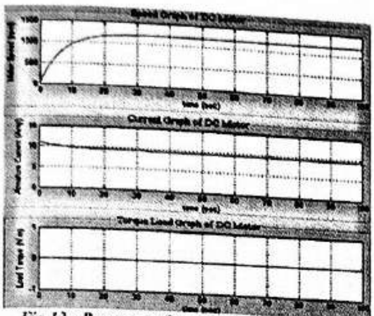

Fig 13 : Response of system without controller for reference speed of 1200 rpm on no-load

A step reference speed of 1200 rpm was randomly selected on no-load. The corresponding responses without load are displayed for without control with controllers are shown in figure 14 and 15.

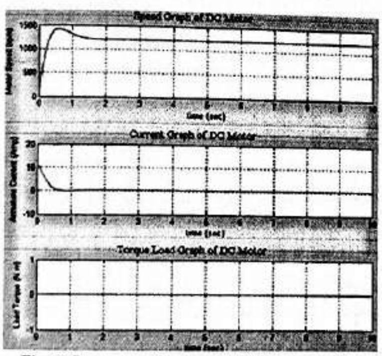

Fig 14 Response of system with PID controller for reference speed of 1200 rpm on-no load

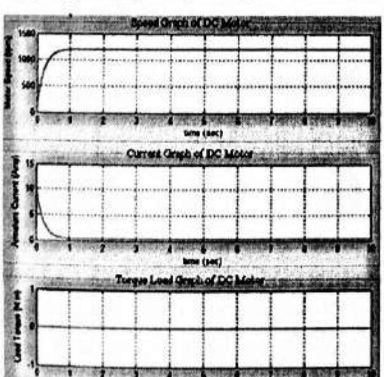

Figure 15 Response of system with FL controller for reference speed of 1200rpm on no- load

The summary of data analysis in figure table V shows the performance indices for the collective time responses of the DC motor without control, with PID control and with FL control displayed in figures 13, 14 and 15 respectively for a reference speed of 1200 rpm on no-load.

Table V : System performance for reference speed of 1200rpm and on no-load

Controller	Rise time Tr (Sec)	Settling time Ts (Sec)	Max. Overshoot (%)	Peak Speed Value (rpm)
Without controller	14.074	25.086	0	1200
With PID controller	0.224	1.387	18.3	1420
With FL controller	0.44	0.781	0	1200

Without control presented in table V, the rise time and the settling time are realized at 14.074 seconds and 25.086 seconds respectively. There is no overshoot hence its peak speed value is at the reference speed of 1200 rpm. The current shoots at the initial stage to 11 Amps and drops to a working current of 9 Amps. This leads to a power dissipation of 923.4 watts.

With PID control presented in figure 14, the rise time and settling time are realized at 0.224 seconds and 1.387 seconds respectively. A maximum overshoot of 18.3% is realized with a peak speed value of 1420 rpm. The current at the initial stage spikes to about 11 Amps and drops within a space of 1second to a working current of about 0.5 Amps. The resultant power is obtained at 2.85 watts.

With FL control presented in figure 15, the rise time and settling time are realized at 0.44 and 0.781 seconds respectively. There is no overshoot hence its peak speed value is at the reference speed of 1200 rpm. The current at the initial stage rises to about 11 Amps and drops to about 0.5 Amps with a power dissipation of 2.85 watts.

(c) System Performance for Reference Speed of 1200 rpm on 7Nm Torque Load

The system response and performance for a reference speed of 1200 rpm without control, with PID control and with FL control on load are presented in figures 16, 17 and 18 respectively.

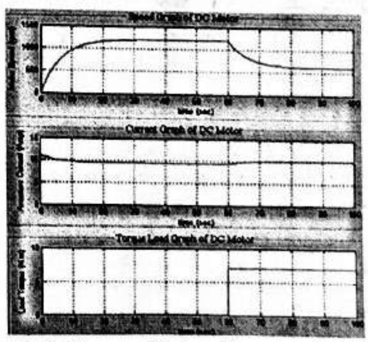

Fig 16 : Response of System without controller for reference speed of 1200rpm on 7Nm torque load.

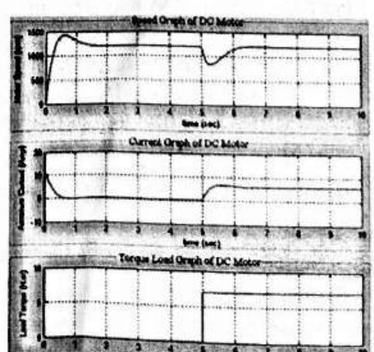

Fig 17: Response of System with PID controller for reference speed of 1200rpm on 7Nm torque load

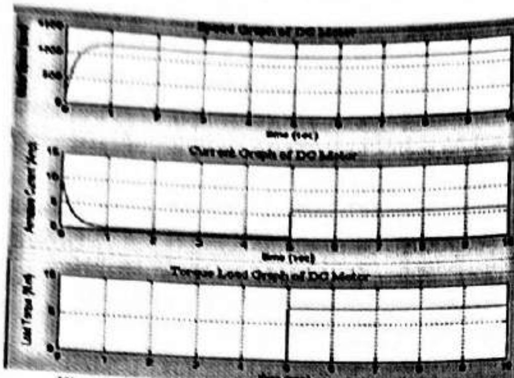

Fig 18: Response of System with FL controller for reference speed of 1200rpm on 7Nm torque load

The summary in Table VI indicates the performance indices for the collective time responses of the DC motor without a controller, with the PID controller and with the FL controller displayed in figures 16, 17 and 18 respectively for a reference speed of 1200 rpm on torque load of 7 Nm.

Table VI System Performance for reference speed of 1200rpm on load of 7Nm

Controller	Rise time Tr (Sec)	Settling time Ts (Sec)	Max. Overshoot (%)	Peak Speed Value (rpm)
Without controller	14.074	-	0	1200
With PID controller	0.224	6.16	18.3	1420
With FL controller	0.44	0.781	0	1200

Without a controller presented in figure 16, the rise time is realized at 14.074 seconds and motor speed is achieved in 25.086 seconds. There is no overshoot hence its peak speed value is at the reference speed. The torque load of 7Nm is applied in 60 seconds and this has a negative effect on the speed of the DC motor which drops to 600 rpm within 25 seconds of applied load. Since the DC motor does not readily adjust to the reference speed, there is no specified settling time. The current initially shoots to 12 Amps and drops to a working current of 9 Amps. On applied load, the current rises from 9 Amps to about 10 Amps and stabilizes after 10 seconds.

With the PID controller presented in figure 17, the rise time is realized at 0.224 seconds and motor speed is achieved in 1.387 seconds. A maximum overshoot of 18.3% is realized with a peak speed value of 1420 rpm. When the 7Nm torque load is applied in 5 seconds, the motor speed drops to 800 rpm then it returns to 1200 rpm within 2 seconds, with a record settling time of 6.16 seconds. The current initially spikes to 11 Amps and drops within 1 second to a working current of about 0.5 Amps. On applied load, the current rises from about 0.5 Amps to 7Amps in less than 1.5 seconds.

With the FL controller presented in figure 18, the rise time is realized at 0.441 seconds and motor speed is achieved in 0.782 seconds. There is no overshoot hence its peak speed value is at the reference speed of 1200 rpm. When the 7Nm load is applied in 5 seconds, the motor speed remains unchanged. The current initially peaks to 11Amps and drops to about 0.5 Amps in one second. On applied load, the current instantly steps up from 0.5 Amps to 6 Amps and remains.

From the foregoing results, it can be observed that at no load and without control, the DC motor has a poor response with regard to rise time, settling time with high power dissipation. When a torque load is applied without control, the DC motor speed drops far below the reference speed. This drop in speed is undesired hence there is need for a controller to be used to reduce this effect.

With PID control, the DC motor at no load operates far better than it does without control due to its faster rise time, settling time and minimal power dissipation.

At an applied load, the DC motor speed decreases to a little margin below reference speed but adjusts quickly to the reference speed in a matter of seconds. However, due to its quick rise time, an undesired overshoot is present in PID control. Fuzzy logic control (FLC) does not display this undesired overshoot. When a torque load is applied to the Fuzzy logic-controlled DC motor, its reference speed significantly remains unchanged. Therefore, in controlling the speed of the DC motor, the FLC performs more effectively than the PID controller due to its faster settling time and its ability to maintain DC motor speed irrespective of the torque load applied. This finding is supported by Bansal and Narvey (2013).

(V) CONCLUSION

This paper successfully presented a comparative analysis on the performance of PID controllers and FL controllers in the control of DC motor speed. The simulation results are obtained using MATLAB/SIMULINK software. The DC motor response is compared without control, with PID control and with Fuzzy logic control. When FL controller response was compared with the conventional PID controller, it was discovered that FL controller shows better performance in terms of zero overshoot and lesser settling time while it exhibits a slightly higher rise time. It is also observed that FL controllers show more robustness and almost insensitive to torque load disturbances than the classical PID controllers. Due to simulation results, the authors recommend that local industries implement the use of fuzzy logic to control the speed of DC motors to enhance their operational capacity as it does not require tuning, compared to Conventional PID controllers. Although FLC response cannot readily predict stability DC motor, for improvement in this area of stability, further researched on control mechanisms such as Adaptive Neuro - Fuzzy Inference System (ANFIS) and optimal control strategy could be used to control DC motor variables such as motor speed and shaft angular position.

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