Adaptive fuzzy logic speed controller for Brushless DC motor

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***Abstract*—A novel method for speed control of brushless dc motor using adaptive fuzzy logic and PI control algorithms has been presented in this paper. Fuzzy logic and PI controllers are formulated and designed using MATLAB toolbox. The parameters such as rise time, peak overshoot, recovery time, settling time and steady state error of a brushless DC motor are taken for analyzing the performance of the proposed controller. The simulation result demonstrated that the response of brushless dc motor with adaptive fuzzy logic shows satisfactory and well damped performance compared to classical PI controller.**

Keywords-PI controller, Fuzzy logic controller, Brushless DC motor, MATLAB/Simulink

I. INTRODUCTION

Brushless DC (BLDC) motors are commonly used in more servo applications in automations, manufacturing, robotics, dynamic actuation, machine tools and positioning devices, due to their advantageous electrical and mechanical features, high torque to volume ratio, high efficiency and low moment of inertia [1-3]. High accuracy is not usually authoritative for most electrical drives, however, in high performance drive applications, an appropriate control performance must be provided even when the parameters of the motor and loads are varying during the motion. Conventional constant gain controllers used in the high performance adjustable speed drives become reduced when the load is nonlinear and, parameter deviations and uncertainties occur. Therefore, control strategy of high performance electrical drives must be adaptive and robust. As a result, interest in emerging intelligent control systems for electrical drives has increased significantly within the last era and numerous intelligent control schemes for brushless DC motors are projected based on linear model [4, 5].

Many varieties of control technique such as Proportional (P), Proportional Integral (PI), Proportional Integral Derivation (PID), adaptive, and Fuzzy Logic Controller (FLC), have been developed for speed control of brushless DC motors. Fuzzy logic, which is based on fuzzy set theory, was first developed by Zadeh in 1965. Control applications such as temperature control, traffic control, DC motor speed control, etc. are the most prevalent of current fuzzy logic applications. For the most complex systems, where few numerical data exist and where only ambiguous or imprecise information is available, fuzzy reasoning provides a way to understand the system behavior by allowing interpreting around between the observed input and the output relations of the system [6-11]. Anti windup Proportional-Integral-Derivative (PID) controller is tested for variable speed motor drives. In this controller the gain is constant, due to that the controller gives oscillatory response during disturbance [6]. The adaptive fuzzy controllers are capable of improving the tracking performance under external disturbances than non adaptive fuzzy controllers [7]. In [8,9] the effectiveness of adaptive fuzzy controllers applied to speed control of permanent magnet DC motor drives experiencing parameter deviations has been outlined. Furthermore, the designed adaptive fuzzy controller for speed control and current harmonics reduction in permanent magnet brushless AC drives also been discussed. The fuzzy logic speed tracking controller designed for brushless DC motor that incorporates attractive properties such as simplicity, good performance and automation has been explained in [10]. The fuzzy controller designed for BLDC motor and effectiveness of fuzzy logic controller has been demonstrated [11]. An experimental approach of fuzzy logic and PI speed control is tested for AC drives. It is clear from the result that the tracking performance of speed is faster in fuzzy logic than PI speed control [12]. In [13], PID, fuzzy PI and fuzzy model reference adaptive control has been considered for experimental study. The study has revealed that, fuzzy logic control outperformed the PID control with regard to overshoot and settling time.

In this paper, adaptive fuzzy logic controller for BLDC motor drive has been proposed. The controller consists of two structures, one is fuzzy PD controller and the other one is fuzzy PI controller. Based on speed error signal received, switching take place between these two controllers. Fuzzy logic tool box under MATLAB environment is used to design the proposed adaptive fuzzy logic controller. This is again integrated with simulink toolbox to perform simulation analysis. Comparison is made between classical PI controller and the proposed adaptive fuzzy controller. Simulation results has been presented to confirm and validity the effectiveness of the proposed controller.

II. DYNAMIC MATHEMATICAL MODEL OF THE BLDC MOTOR DRIVE

Typical inverter system for a BLDC motor and the other related equations for obtaining the mathematical model are taken from [14, 15]. The BLDC motor is connected to the output of the inverter as shown in fig.1. The inverter input terminals are connected to constant supply voltage. It is

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assumed that there are no power losses in the inverter and the motor winding is connected in star.

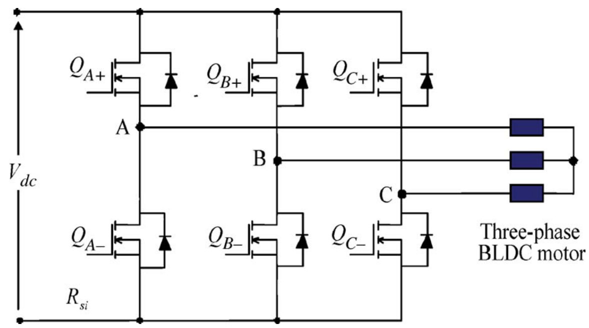


Figure.1. Typical inverter system for a BLDC motor.

For a symmetrical winding of motor and assuming balanced supply system, the voltage equation across the motor winding is expressed as,

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \tag{1}$$

$$V_b = R_b i_b + L_b \frac{di_b}{dt} + M_{ba}\frac{di_a}{dt} + M_{bc}\frac{di_c}{dt} + e_b \tag{2}$$

$$V_c = R_c i_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \tag{3}$$

Where V_a,V_b and V_c denotes phase voltage of the motor. R_a, R_b and R_c represents stator winding resistances. Phase current of the motor are represented by i_a, i_b and i_c. Self inductance of the motor winding is represented by L_a, L_b and L_c and the mutual inductances between stator windings are denoted by M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca} and M_{cb} respectively.

The back-EMF waveforms e_a, e_b and e_c are the functions of angular velocity of the rotor shaft, so

$$e = k_e * \omega_m \tag{4}$$

Where K_e is the back-emf constant.

Considering the above equation, the BLDC motor mathematical model can be represented by the following equation in matrix form,

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

If is assumed that the rotor has a surface-mounted design, which is generally the case for today's BLDC motors. Also there is no saliency such that the stator self inductances are independent of the rotor positions and hence,

$$L_a = L_b = L_c = L$$

And the mutual inductances will have the form as given below,

$$M_{ab} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M$$

Assuming three phase balanced system, all the phase resistances are equal. Therefore,

$$R_a = R_b = R_c = R$$

Rearranging the equation (5) after incorporating the above assumption yields,

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{6}$$

The electromechanical torque is expressed as

$$T_{em} = J\frac{d\omega_r}{dt} + B\omega_r + T_L \tag{7}$$

Where J, B and ω_r are denotes the moment of inertia, frictional coefficient and angular velocity of the motor respectively. T_L is the load torque.

Since the electromagnetic torque of 3-phase BLDC motor is dependent on the current, speed and back-EMF waveforms, the equation for instantaneous electromagnetic torque (7) can be modified and represented as,

$$T_{em} = \frac{1}{\omega_m}\left(e_a i_a + e_b i_b + e_c i_c\right) \tag{8}$$

III. ADAPTIVE FUZZY LOGIC CONTROLLER DEVELOPMENT

Fuzzy PI controllers are chosen than fuzzy PD controllers as fuzzy PD controllers are not able to eliminate steady state errors. However, fuzzy PI controllers show poor performance during the transient period [13]. In order to improve the performance during transient and steady state phase adaptive fuzzy logic controller has been developed. The proposed adaptive fuzzy logic controller for BLDC motor is shown in fig.2.

The proposed controller consists of two controller structure namely fuzzy PD controller and fuzzy PI controller. Based on the error signal received, switching takes place between these controllers accordingly. Fig.3 shows the architecture of the proposed adaptive fuzzy logic controller. The fuzzy PI and fuzzy PD controller has the following features,

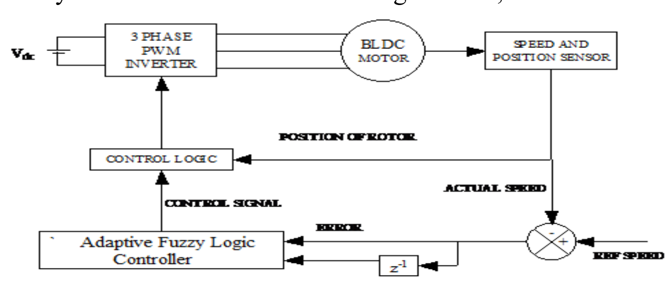


Figure.2. Proposed adaptive fuzzy logic controlled BLDC motor.

1. It has the similar linear structure as that of the conventional PI & PD controller, but has non-constant coefficient and self-tuned control gains (they are the nonlinear functions of the input signal).
2. The controller is designed based on the classical discrete PI-PD controller, from which the fuzzy control law is derived.
3. The fuzzy PI and fuzzy PD controller has extraordinary performance in the case of time-delay and nonlinear systems.
4. The fuzzy PI controller improves the steady state response of the system and minimizes the steady state error.
5. The fuzzy PD controller improves the transient response of the system and minimizes the rise time.
6. It is anticipated to accommodate the robust stabilization and disturbance rejection problems.

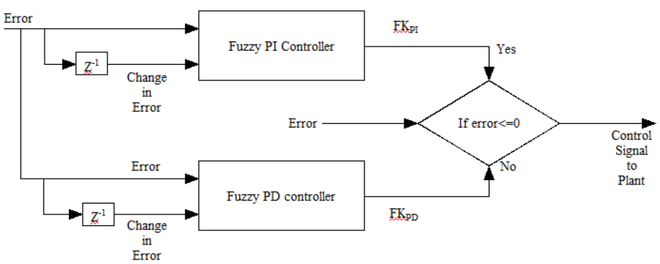


Figure. 3. Architecture of the proposed adaptive fuzzy logic controller.

A. *Fuzzy-Based Proportional Integral Controller*

The first step in designing the controller is to decide which state variables of the drive system may be taken as the input signals to the controller. Both the speed error and change in speed error are used as the inputs to the speed controller. The output of the fuzzy-based proportional integral controllers is the gain FK_{PI}. The linguistic fuzzy variable “error” has seven sets: positive big (PB), positive medium (PM), positive small (PS), zero (ZE), negative small (NS), negative medium (NM) and negative big (NB), with each set having its own membership function. Furthermore, the linguistic fuzzy variable “change in speed error” has also seven sets: PB, PM, PS, ZE, NS, NM and NB, with each set having its own membership function. After specifying the fuzzy sets, it is required to determine the membership functions for seven sets. Typical triangular membership functions are utilized for the determination of error and change in speed error. The following fig.4 shows the membership functions for the fuzzy inputs. The seven fuzzy sets can be symbolized by F_i^j, where i = 1, 2 and j = 1, 2, 3…7. Their corresponding membership functions can be symbolized by μF^j (e(k), ce(k)), where j = 1, 2, 3…7.The next step in the design of the fuzzy controller is the determination of the fuzzy IF–THEN inference rules. The number of fuzzy rules that are required is equal to the product of the number of fuzzy sets that make up each of the two fuzzy input variables.

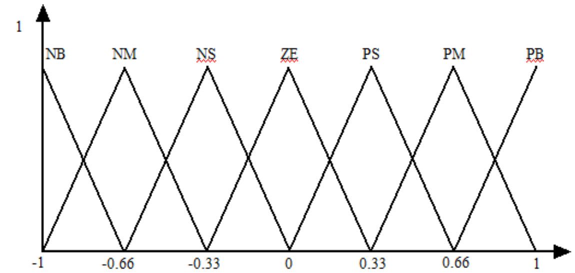


Figure.4. Membership functions for e (k) and ce (k).

Thus, a total of fourty nine fuzzy rules are required to relate each possible combination of the two fuzzy input variables to the output membership fuzzy sets. The fuzzy rules ensure that the output of each fuzzy controller enhances the overall speed tracking performance. Fig.5 shows rule base for fuzzy PI controller. Examples of such rules are as follows,

1) IF e (k) is PB and ce (k) is NB, THEN FK_{PI} is zero (ZE).
2) IF e (k) is NL and ce (k) is NS, THEN FK_{PI} is positive big (PB).
3) IF e (k) is PB and ce (k) is PB, THEN FK_{PI} is negative big (NB).

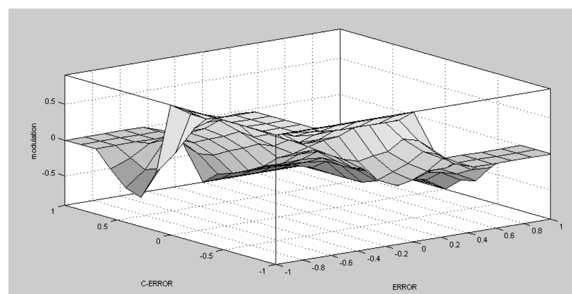


Figure.5. Rule base for fuzzy PI controller.

In general, a typical fuzzy rule is of the form as given below,

R (k): IF e (k) is F_1^j and ce (K) is F_2^l THEN f_{PI} is C_{lk} for j = 1. . . 7; l = 1. . . 7; k = 1. . . 49.

The conjunction of the rule antecedents is evaluated by the fuzzy operation intersection, which is implemented by the min operator. The rule strength represents the degree of membership of the output variable for a particular rule. Defining the rule strength, $\xi_{i,j}$ of a particular rule as

$$\xi_{i,j} = \min(\mu F_i, \mu F_j) \qquad (9)$$

Where μF_i and μF_j are the membership functions of e (k) and ce (k) respectively. i ∈ [PB, PM, PS, ZE, NS, NM and NB] is associated with the fuzzy variable e(k), and j ∈ PB, PM, PS, ZE, NS, NM and NB] is associated with the fuzzy variable ce (k). The fuzzy inference engine uses the appropriately designed knowledge base to evaluate the fuzzy rules and produce an output for each rule. Subsequently, the multiple outputs are transformed to a crisp output by the defuzzification interface. Once the aggregated fuzzy set representing the fuzzy output variable has been determined, an actual crisp control decision must be made. The process of decoding the output to produce an actual value for the controller gain FK_{PI} is referred to as defuzzification. Thus, a fuzzy logic controller based center-average defuzzifier is implemented. The output of fuzzy-based proportional integral controller is given by,

$$FK_{PI} = f_{PI}\left(e(k), ce(k)\right) \tag{10}$$

Where f_{PI} denotes the centre-average defuzzifier and it is given by,

$$= \frac{\sum_{l=1}^{49} \mu_o^{\,l}\left(\min\left(\mu F_i^l\left(e(k), ce(k)\right)\right)\right)}{\sum_{l=1}^{49}\left(\min\left(\mu F_i^l\left(e(k), ce(k)\right)\right)\right)}$$

The linguistic fuzzy output variable "FK_{PI}" has seven sets: PB PS, PM, ZE, ZS, ZM and ZB. After specifying the fuzzy sets, it is required to determine the membership functions for these sets $\mu_O^{\,l}$ for l = 1. ......7. The membership function for the fuzzy set is represented by triangular function. Fig.6 shows the resulting membership functions for the variable FK_{PI}.

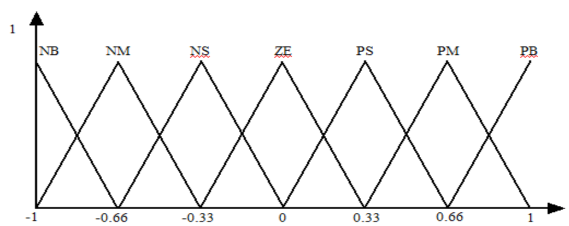


Figure.6. Membership functions for FK_{PI}.

Consequently, the control signal generated by the fuzzy proportional integral controller can be written as

$$u_{FPI}(k) = G_P\left\{f_P\left(e(k), ce(k)\right)\right\}e(k) + G_I\left\{f_I\left(e(k), ce(k)\right)\right\}\sum_{i=0}^{k} e(i)\Delta t \tag{11}$$

Where G_P and G_I are scaling factors of the fuzzy PI controller.

B. Fuzzy-Based Proportional Derivative Controller

The same methodology applied to fuzzy-based proportional integral controllers is followed for fuzzy-based proportional derivative controller also. The input signals (state variables) to the controller are e(k) and ce (k). The output of the controller is the gain FK_{PD}. After specifying the fuzzy sets and the membership functions for seven sets, the triangle membership functions are also used to define the degree of membership. Figure.4 shows the membership functions for the fuzzy set. Similarly, the linguistic fuzzy output variable "FK_{PD}" has seven sets: PB, PM PS, ZE, ZS, ZM and ZB. The same triangular membership functions shown in figure.6 are utilized for these fuzzy sets also. Figure.7 shows rule base for fuzzy PD controller. Consequently, the output of fuzzy-based proportional derivative controller is given by

$$FK_{PD} = f_{PD}\left(e(k), ce(k)\right) \tag{12}$$

Where f_{PD} denotes the centre-average defuzzifier and it is given by,

$$= \frac{\sum_{l=1}^{49} \mu_o^{\,l}\left(\min\left(\mu F_i^{\,l}\left(e(k), ce(k)\right)\right)\right)}{\sum_{l=1}^{49}\left(\min\left(\mu F_i^{\,l}\left(e(k), ce(k)\right)\right)\right)}$$

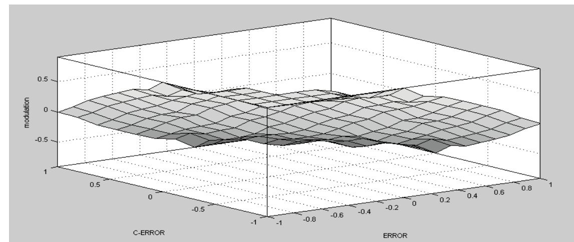


Figure.7. Rule base for fuzzy PD controller.

The control signal of the fuzzy-based proportional derivative controller is given by,

$$u_{FPD}(k) = G_P\left\{f_P\left(e(k), ce(k)\right)\right\}e(k) + G_D\left\{f_D\left(e(k), ce(k)\right)\right\}\frac{\Delta e(k)}{\Delta t} \tag{13}$$

Where G_P and G_D are scaling factors of the fuzzy PD controller.

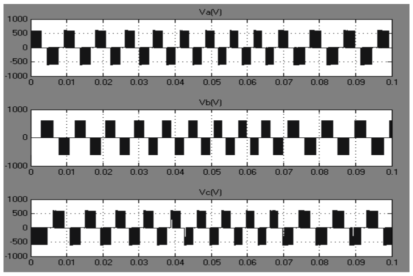
IV. SIMULATION RESULTS AND DISCUSSION

In order to validate the proposed control strategies described above, digital simulations has been carried out for the BLDC motor drive system using MATLAB/SIMULINK. The specifications used for the BLDC motor drive system is given in the following Table. I.

Fig.8 (a) shows simulation result of the phase voltage waveforms based on the rotor position at 1500 rpm. The phase difference between V_a, V_b and V_c is approximately 120^0. Fig.8 (b) shows simulation result of the phase current waveforms based on the rotor position at 1500 rpm. The peak current value is approximately 50 A for all I_a, I_b and I_c.

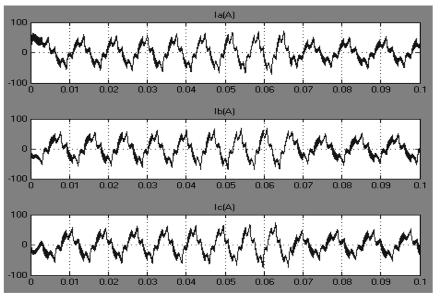
Table. I Selected specifications of BLDC Motor drive

Specifications	Value
Stator phase resistance R (ohm)	3
Stator phase inductance L (H)	0.001
Flux linkage established by magnets (V.sec)	0.175
Voltage Constant (V/rpm)	0.1466
Torque Constant (N.m / A)	1.4
Moment of Inertia (kg.m^2/rad)	0.0008
Friction factor (N.m/(rad/sec))	0.001
Pole pairs	4



(a)

Figure.8. (a) Phase voltage waveforms based on the rotor position at 1500 rpm



(b)

Figure.8 (b) Phase current waveforms based on the rotor position at 1500 rpm

A. *Response of the Drive for Constant Load Condition*

Simulation results of speed and torque response of BLDC motor using classical PI controller is shown in fig.9 (a) and using the proposed adaptive Fuzzy logic Controller is shown in fig.9 (b). The simulation result has been obtained by keeping the reference speed at 1500 rpm and the load torque constant at 25 Nm.

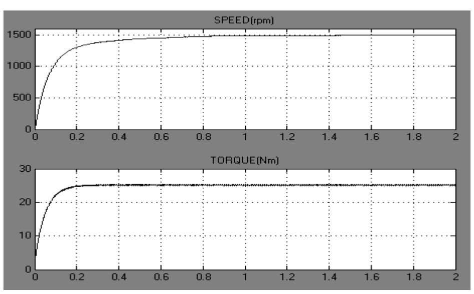


Figure.9. (a) Speed and torque response of BLDC motor for PI controller

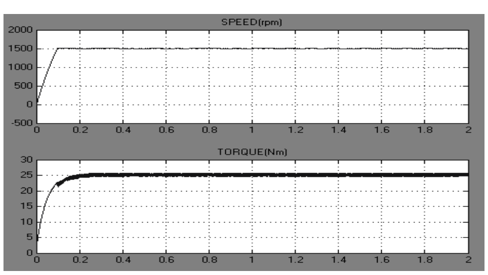


Figure. 9. (b) Speed and torque response of BLDC motor for proposed controller

From the response plots shown above, if the PI controller is used, the drive attains the set or reference speed in 1 second. If the proposed adaptive fuzzy logic controller is used, reference speed is reached in 0.1 second. Also, the other response parameters like rise time, settling time and steady state error are compared and presented in Table. II for both PI and adaptive fuzzy logic controllers.

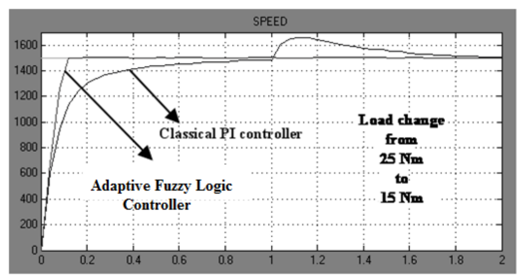
Table. II Comparison of Response parameters for constant load

Parameters	PI controller	Proposed adaptive fuzzy logic controller
Rise time (sec)	0.4	0.08
Settling time (sec)	1.0	0.1
Steady state error (rpm)	3.5	3.5

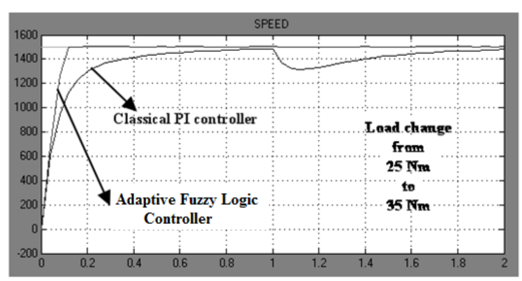
From the results shown above, even though the steady state error is same for both controllers, the other vital performance indexes are in favour of proposed controller only. With the newly developed controller, the drive system will have superior rise time and settling time characteristics.

B. *Response of the Drive Under varying Load Condition*

Any drive, as most of the application demands, it has to perform under varying load conditions. Therefore, in order to ascertain the superior performance of the proposed adaptive fuzzy logic controller, simulation results has been obtained for varying load conditions also. First, the load torque is decreased from 25 Nm to 15 Nm and then it is increased to 35 Nm. The following fig. 10 shows the response for both varying load conditions.



(a)



(b)

Figure.10. Comparison of classical PI and proposed controller for varying load conditions (a) Load change from 25 Nm to 15 Nm (b) Load change from 25 Nm to 35 Nm

The important parameters like percentage peak overshoot, percentage peak undershoot and steady state error is compared for the both controllers and the results are shown in the Table.III. Following sudden load change, any system will take sufficient time to adjust before tracking and settling at set speed. This is termed as recovery time and it becomes the testing ground for judging the performance of any controller. A good controller should be able to restore the system to set value in the shortest possible following any disturbance. The recovery time is also compared for both controllers designed for BLDC motor drive and presented below. Case A represents decrease in load torque from 25 Nm to 15 Nm and Case B represents increase in load torque from 25 Nm to 35 Nm.

Table. III Comparison of Response parameters for varying load conditions

Parameters	Load conditions	PI controller	Proposed adaptive fuzzy controller
Percentage peak overshoot	Case A	13	0.17
	Case B	-	-
Percentage peak undershoot	Case A	-	-
	Case B	12	0.54
Steady state error (rpm)	Case A	8	3.5
	Case B	20	6
Recovery time (sec)	Case A	2.0	0
	Case B	2.2	0

From the results, it is clear that, the proposed adaptive fuzzy logic controller for the BLDC motor drive is superior in all aspects when compared with PI controller. When the load is increased or decreased, the proposed controller does not produce any undershoot or overshoot. Also, zero recovery time indicates that, the proposed controller is well suited for the drives employed for varying load conditions.

V. Conclusion

An efficient controller has been proposed for the brushless DC motor drive. The proposed controller i.e., adaptive fuzzy logic controller has been compared with classical PI controller under constant and varying load conditions. Various control system parameters such as steady state error, rise time, peak overshoot, recovery time and settling time for both controllers has been measured, analyzed and compared. The result reveals that the control concept with adaptive fuzzy logic controller outperforms classical PI controller in all aspects.

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