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High Performance Fuzzy Adaptive PID Speed Control of a Converter Driven DC Motor

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Abstract

For a large variety of Industrial applications dc motors are being used. The common requirement of the drives in industries is speed control under varying operating conditions. In several research studies, the controllers have been considered without modeling of final control element (FCE). In practical applications, the effect of dynamics and nonlinearity of FCE affects the performance of the system, so it is necessary to consider these for a dependable simulation study of the drive performance. The overall system becomes non-linear due to the dynamics of converter used as FCE. In this study a new approach is being used, first the transfer function of the buck converter is obtained by considering a small linear region near the operating point, then using overall transfer function of buck converter and dc motor, the PID settings are obtained. Now fuzzy logic is used to update these settings on-line corresponding to the changes that may occur in system operating conditions. This configuration of controller is also observed to have robust performance against parameter variations and uncertainties. For more close to actual performance evaluation PWM controlled buck converter, used as FCE has been simulated using sim-power system library of MATLAB. The comparative results are presented with PID and fuzzy adaptive PID control strategies implemented, for both types of control situations i.e. tracking speed control and load disturbance rejection and the strength of approach is demonstrated.

Keywords: *dc drives, fuzzy logic, PID controller, buck converter, state space averaging model and small signal model of converter*

1. Introduction

The dc motor is controllable over a wide range with stable and linear characteristic and is therefore a common choice in the industrial drives [1, 3]. For tracking control problems dc motor is ideally suited [4, 8] and this can be achieved by varying the motor input voltage easily and over a wide range. Fuzzy logic controllers have been widely used in manufacturing and process control system problems. Fuzzy-PID control techniques have been discussed in detail with examples [9, 16]. Fuzzy PID type controllers have been discussed in [17] with linear plant transfer function for control. Self tuning fuzzy type PID controller has been discussed in [18] for control of magnetic bearing. Mohan and Sinha [19] proposed a two term fuzzy controller structure. This structure has been discussed with BIBO stability condition but no practical simulation results have been included. A self tuning fuzzy type PID controller has been discussed and used in [20], which is applied on a linear plant with some uncertainty in the plant parameters. In most research studies the performance measures have not been considered in detail.

The advantage of fuzzy logic for online tuning of PID controller has been used in this study to obtain robust speed control of a dc motor with an accurately modeled buck converter.

In several studies [21, 24] the final control element has not been considered leading to optimistic results, but not suitable for implementation. The buck converter is often used as a final control element (FCE) to provide the power to armature to affect the speed of motor as per desired tracking or to offer a good disturbance rejection property under load variations. It is a dc-dc switching converter which introduces non-linearity and ripples in the output [25]. The overall system becomes nonlinear and thus not amenable to transfer function approach. The converter can be modeled with reasonable accuracy at every operating point, yet difficult to linearise though the effects of nonlinearity can be minimized by using the two energy storing elements, i.e. inductor and capacitor. The authors of [21, 24] have suggested a design method of PID controller but without considering the dynamics of the converter i.e. the final control element, resulting in an optimistic high performance. In [26, 27] the comparative studies of buck converter driven dc motor have been conducted for PI and fuzzy-PI, PI and LQR controllers. The nonlinearity involved in the buck converter is neglected and the transfer function has been used in the simulation.

In this paper the inaccuracies noted in earlier studies have been considered and a more realistic performance improved by the online fuzzy tuning has been developed. The buck converter has been designed with much improved model, as the final control element for the dc motor considered, is simulated in MATLAB environment.

Also, a different approach is attempted for modeling as well as for control. The transfer function of the buck converter is obtained by considering a small linear region near its operating point. Using the state space averaging model and small signal model the transfer function of the converter is obtained. The dc motor model is developed using the dynamic equations [28] and the speed to voltage transfer function of the dc motor are obtained. The transfer function of converter has been obtained only to get the settings of PID controller to start with, and for simulation a practical model of buck converter is implemented using Sim-power library of MATLAB. This approach provides results closest to the expected ones in a real situation.

The overall transfer function of buck converter with dc motor is used to apply Z-N method [34] to obtain the initial PID settings. Then a proposed fuzzy logic is used to update these controller settings on-line, corresponding to the changes that may occur in the system operating conditions. This configuration of controller has also been observed to have robust performance against parameter variations and uncertainties. The comparison of results are presented with PID tuning by Zeigler-Nichols approach [29] and proposed fuzzy adaptive PID control strategy, for both types of control situations i.e. tracking speed control and load disturbance rejection.

The overall concept can be understood with the help of the block diagram of the control scheme presented in Figure 1.

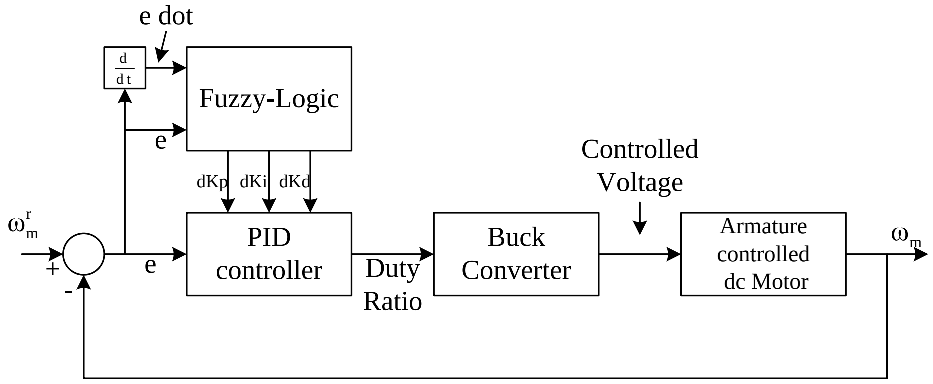

Figure 1. Block Diagram of PID Controlled Buck-Converter-Driven-dc Motor

The paper is organized as follows: Second section outlines the design and modeling of buck-converter being used as the final control element for the chosen dc motor. In section III the dc motor transfer function model and PID gain settings are obtained using Z-N method. Section IV presents the design of fuzzy logic based PID controller for the overall nonlinear control system for the dc motor drive. The simulation results are presented in section V and conclusions are brought out in section VI.

2. Design and Modeling of Final Control Element

In this section design equations and transfer function model of final control element (buck converter) are described.

2.1. Buck Converter Design [25]

The configuration chosen for buck converter is shown in Figure 2.

Output equation of the buck converter, in terms of the input voltage V_d and duty ratio D of the switch is given by:

$$V=DV_d$$

The design of buck converter is based on the output voltage (V), maximum allowed ripple in the output (ΔV_c) and maximum allowed ripple in the current (ΔI_L). Based on these specifications to be met, the buck converter parameters can be obtained as follows.

The value of inductance: $$L = \frac{D\, V_d\, (1 - D)}{f\, \Delta I_L}$$

and, the capacitance can be calculated as: $$C = \frac{D\, V_d\, (1 - D)}{8\, L\, f^2\, \Delta V_C}$$

For continuous conduction of the converter there must be a check, which can be performed by verifying the values of inductance and capacitance. i.e.

$$L > \frac{(1\text{-}D)\,R}{2f} \quad ; \quad C > \frac{(1\text{-}D)}{16\,L\,f^2}$$

2.2. Modeling and Transfer function of Buck Converter

The modeling for the two modes of operation and the transfer function of final control element – the buck-converter for use in this strategy, can be achieved in a systematic manner through the following steps:

2.2.1. State Space Averaging Model of Buck Converter: The circuit diagram of a buck converter is shown in the Figure 2. In state space averaging model both the modes of operation (i.e. switch ON and OFF modes) are considered and an averaging model is developed so as to take both modes into consideration.

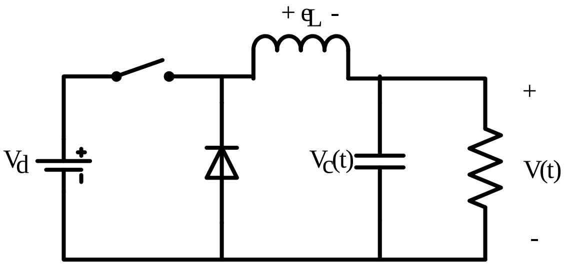

Figure 2. Buck Converter Configuration

ON mode: When switch is ON, the diode behaves like an open circuit. The circuit configuration is shown in Figure 3.

The dynamic equations can be written as:

$$L\frac{di_L}{dt} = V_d - v_c$$

$$\frac{di_L}{dt} = \frac{1}{L}V_d - \frac{1}{L}v_c \qquad (1)$$

$$C\frac{dv_c}{dt} = i_L - i_R$$

$$\frac{dv_c}{dt} = \frac{1}{C}i_L - \frac{1}{C}i_R \qquad (2)$$

So the state-space form in the ON mode of the buck converter will be:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} v_d$$

$$\dot{x} = A_1 x + B_1 u$$

$$y = v = v_c = C_1 x = \begin{bmatrix} 0 & 1 \end{bmatrix} x$$

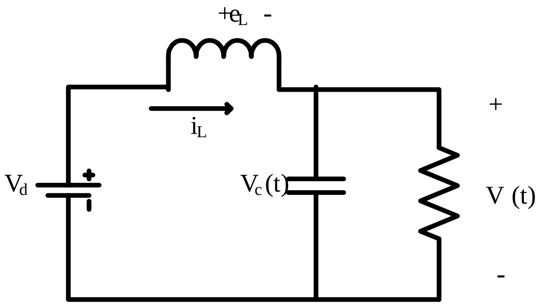

Figure 3. Buck Converter Circuit in ON Mode

OFF mode: The diode behaves like a short-circuited path when switch is in OFF mode and the input source appears disconnected from the circuit. Figure 4. shows the circuit diagram of the buck converter in OFF mode. The dynamic equations in this mode can be written as:

$$L\frac{di_L}{dt}=-v_c$$

$$\frac{di_L}{dt}=-\frac{1}{L}v_c \tag{3}$$

$$C\frac{dv_c}{dt}=i_L-i_R$$

$$\frac{dv_c}{dt}=\frac{1}{C}i_L-\frac{1}{C}i_R \tag{4}$$

So the state-space form in the OFF mode of the buck converter will be:

$$\begin{bmatrix}\dot{i}_L\\ \dot{v}_c\end{bmatrix}=\begin{bmatrix}0 & -1/L\\ 1/C & -1/RC\end{bmatrix}\begin{bmatrix}i_L\\ v_c\end{bmatrix}+\begin{bmatrix}0\\ 0\end{bmatrix}v_d$$

$$\dot{x}=A_2\ x+B_2\ u$$

$$y=v=v_c=C_2x=\begin{bmatrix}0 & 1\end{bmatrix}x$$

Let the duty ratio of converter to be d. Then we can define:

$$A=A_1\ d+A_2\left(1\text{-}d\right)$$

$$B=B_1\ d+B_2\left(1\text{-}d\right)$$

$$c=C_1\ d+C_2\left(1\text{-}d\right)$$

In case of buck converter

$$A = A_1 = A_2 = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}$$

$$B = B_1 d = \begin{bmatrix} 1/L \\ 0 \end{bmatrix} d \qquad c = C_1 = C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

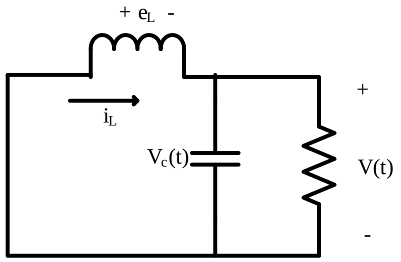

Figure 4. Buck Converter Circuit Diagram in OFF Mode

2.2.2 Small Signal Model and Transfer Function: Using small signal model of the converter the input transfer function and the control transfer can be obtained [30]. Here we are controlling the converter output voltage by varying the duty ratio, so the control transfer function has to be obtained. By using the control transfer function of the converter for small changes, the gain settings of the PID controller can be obtained. In this range the converter can be considered linear.

$$\dot{x} = A x + B u$$

$$\dot{x} = \left[A_1 d + A_2 (1\text{-}d)\right] x + \left[B_1 d + B_2 (1\text{-}d)\right] u \tag{5}$$

$$y = cx$$

$$y = \left[C_1 d + C_2 (1\text{-}d)\right] x \tag{6}$$

Considering small perturbations in duty-ratio and input voltage, as:

$$d = D + \tilde{d};\ v_d = V_d + \tilde{v}_d$$

Hence, $x = X + \tilde{x}$ and $v = V + \tilde{v}$
Under steady-state condition,

$$\dot{X} = A X + B V_d = 0$$

By putting these values into equations (5) and (6) with assumption that the products of perturbations are neglected, it is possible to obtain

$$\dot{\tilde{x}} = A\,\tilde{x} + B\,\tilde{v}_d + F\,\tilde{d}$$

where,

$$F = \left[\left(A_1 - A_2\right)X + \left(B_1 - B_2\right)V_d\right]$$

$$v = c\tilde{x} + \left(C_1 - C_2\right)\,X\,\tilde{d}$$

and, Control Transfer Function for buck- converter would be:

$$\frac{\tilde{v}(s)}{\tilde{d}(s)} = c\,\left(s\,I - A\right)^{-1}\,F$$

or, $$\frac{\tilde{v}(s)}{\tilde{d}(s)} = \frac{V_d / LC}{s^2 + s/RC + 1/LC}$$

This converter transfer function (TF) has been used with dc motor TF to calculate initial PID settings using Z-N method.

3. Modeling of dc Motor and Initial Tuning of PID Controller

Modeling of dc drive and determination of PID controller settings using Z-N method are presented in this section.

3.1 Modeling of dc Motor

For the separately excited dc motor model [28] considered for study as shown in Figure 5. The voltage equation of the armature circuit under transient is given by:

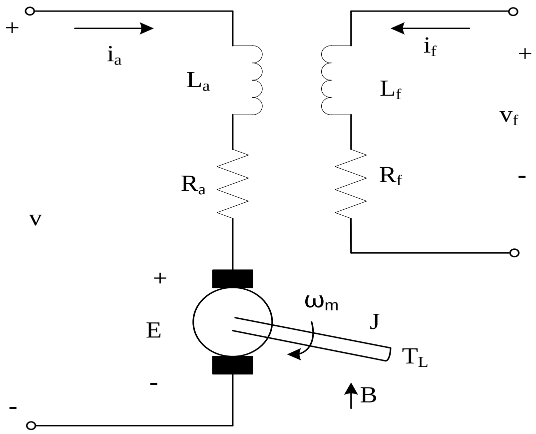

Figure 5. Separately Excited dc Motor

$$v = R_a\ i_a + L_a \frac{di_a}{dt} + K\,\omega_m \tag{7}$$

Here, $K = K_e\ \Phi$

From the dynamics of motor- load system

$$J\frac{d\omega_m}{dt} = T - T_L - B\omega_m$$

Here, $T=Ki_a$

So $$J\frac{d\omega_m}{dt} = K\,i_a - T_L - B\,\omega_m$$

Differentiating the above equation:

$$K\frac{di_a}{dt} = J\frac{d^2\omega_m}{dt^2} + B\frac{d\omega_m}{dt} + \frac{dT_L}{dt} \tag{8}$$

Substituting from equation 7 for di_a/dt into equation 8, and rearranging the terms gives:

$$\tau_a\frac{d^2\omega_m}{dt^2} + \left(1+\frac{\tau_a}{\tau_{m1}}\right)\frac{d\omega_m}{dt} + \frac{1}{\tau_{m2}}\omega_m = \frac{Kv}{JR_a} - \frac{1}{J}\left(T_L + \tau_a\frac{dT_L}{dt}\right) \tag{9}$$

Taking Laplace transform of equation (9):

$$\omega_m(s) = v\frac{\left(K/R_a\right)}{J\left[s^2\tau_a + s\left(1+\frac{\tau_a}{\tau_{m1}}\right) + \frac{1}{\tau_{m2}}\right]} - T_L\frac{1+s\tau_a}{J\left[s^2\tau_a + s\left(1+\frac{\tau_a}{\tau_{m1}}\right) + \frac{1}{\tau_{m2}}\right]} \tag{10}$$

where,

$$K = K_e\ \Phi\ ;\ K_e = \frac{PZ}{2\pi A}\ ;\ \tau_a = \frac{L_a}{R_a};\ \tau_{m1} = \frac{J}{B}\ ;\ \tau_{m1} = \frac{JR_a}{\left(BR_a + K^2\right)}$$

For the conduct of a case study and compare the performance of the proposed fuzzy approach for control with PID controlled drive, a separately excited dc motor with nameplate ratings of 1HP, 220 V, 550 rpm has been used in simulation.

Following parameter values are associated with it [15].

Moment of Inertia, J = 0.068 kg-m2 or Nm/ (rad/sec2); Coefficient of viscous friction, B=0.03475 Nm-sec or Nm/(rad/sec); Armature resistance, Ra=7.56 ohms; Armature circuit inductance, La = 0.055 Henry; K = 3.475 V/rad/sec; τ_a=0.00727 Sec; τ_{m1}=1.9568 Sec; τ_{m2}=2 Sec. With full load torque of 12.95 Nm.

By substituting the parameter values in the equation (10), the speed of the motor can be expressed as a function of supply voltage and load torque as:

$$\omega_m(s)=\frac{929.8}{s^2+138s+3354.91}V(s)-\frac{14.7s+2022.81}{s^2+138s+3354.91}T_L(s)$$

A block diagram is developed to represent dc motor and shall be used for simulation study.

3.2 Determination of PID Controller Settings

Z-N method is an empirical approach to determine the PID controller settings for a system, perfected over a long period in process control systems, and used successfully [29] in large number of industrial problems. Using ultimate gain and period three PID parameters Kp, Ki and Kd of the controller are obtained. By using the available tuning rules the controller parameters can be obtained, for initial setting of controller.

4. Design of Fuzzy Logic based PID Controller

Fuzzy logic is a problem solving technique in control system which uses if else logic. Fuzzy concept was introduced by Zadeh [32]. This concept is based on partial set membership rather than crisp set membership. Adaptation of this logic is used here for online tuning of PID and referred as fuzzy logic based PID controller. Fuzzy-PID has been widely used in the research [9, 16] due to its major advantage over conventional PID controller, the capability to update the controller parameters in real- time whereas in conventional PID parameters are fixed.

4.1 Fuzzy Rules for Adaption of PID Controller Parameters

Fuzzy rules in the present strategy are devised to update the controller parameters based on variations in error and the rate-of-change of output error at each step. Tables (1-3) show the fuzzy rule tables for incremental changes to be made in controller parameters at every step i.e. dKp, dKi and dKd for online updation during transient periods. The philosophy of generating these rules for fuzzy-PID is case based reasoning (CBR) approach and shall be according to the requirements of the case based on experience. In the present study, these rules have been generated by considering the concept of rule surfaces for PID tuning [33]. The effectiveness of fuzzy rules near zero error regions has been discussed [34] in detail. A total of 49 fuzzy rules were considered necessary and created to implement the proposed Fuzzy-PID controller for dc- drive system in this simulation study. Each rule uses an If – Then logic of the following form:

If **E** is NL and **ED** is NL then **dKp** is PL, **dKi** is NL and **dKd** is NL.

Using these rules the fuzzy rule tables have been developed for each PID parameter. The inputs of the fuzzy logic block are the speed error (E) and derivative of error (ED). Using these inputs and after applying the fuzzy rules, it provides the output increments dKp, dKi and dKd, which are used to update the PID controller gains online.

Table 1. Fuzzy Rule Table for Change in Kp

E\ED	NL	NM	NS	ZE	PS	PM	PL
NL	PL	PL	PL	PL	PL	PL	PL
NM	PS	PM	PM	PM	PM	PM	PS
NS	ZE	ZE	PS	PS	PS	ZE	ZE
ZE	NL	NS	ZE	ZE	ZE	NS	NL
PS	ZE	ZE	PS	PS	PS	ZE	ZE
PM	PS	PM	PM	PM	PM	PM	PS
PL	PL	PL	PL	PL	PL	PL	PL

Table 2. Fuzzy-rule Table for Change in Ki

E\ED	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	NM	NL	NL	NL	NL	NL	NM
NS	PM	ZE	NM	NL	NM	ZE	PM
ZE	PL	PM	PS	NL	PS	PM	PL
PS	PM	ZE	NM	NL	NM	ZE	PM
PM	NM	NL	NL	NL	NL	NL	NM
PL	NL	NL	NL	NL	NL	NL	NL

Table 3. Fuzzy Rule Table for Change in Kd

E\ED	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	ZE	NS	NM	NM	NM	NS	ZE
NS	PS	ZE	ZE	ZE	ZE	ZE	PS
ZE	PL	PL	PM	PS	PM	PL	PL
PS	PS	ZE	ZE	ZE	ZE	ZE	PS
PM	ZE	NS	NM	NS	NM	NS	ZE
PL	NL	NL	NL	NL	NL	NL	NL

4.2 Rule Surfaces

Fuzzy Rule surface shows the region in which the fuzzy rules have been made more effective. Fuzzy rules can be understood by the fuzzy rule surface, it shows the values of PID gains at the various points of inputs. The inputs and outputs are normalized to -1 to +1. Rule surface is helpful to see the effect of change in input to output in each direction (positive and negative). In other words how the output changed corresponds to change in input. Figures (6-8) show the rule surfaces for dKp, dKi and dKd.

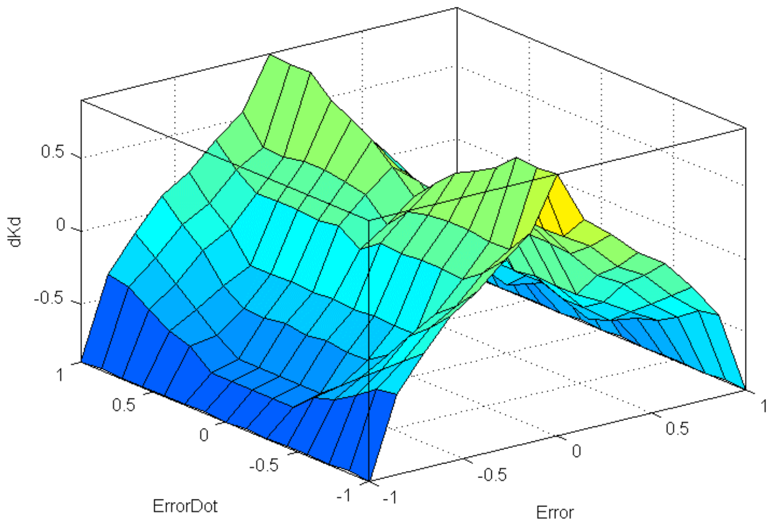

Figure 8. Fuzzy Rule Surface for dKd

It is observed that near error –zero- region (or near stable region) most of the fuzzy rules are made and the rules are almost same for all values of error dot (ED) as error increases in either direction.

5. Simulation Results

The results below provide the comparison between the two, PID tuning approaches – the classical Z-N method and the one using proposed fuzzy- adaptive approach. The motor has been started at no-load then full load has been applied on the motor (after 0.5 sec) and motor is allowed time to attain the rated full-load speed before any of the disturbance is introduced.

5.1. Set-point Tracking Control

+5 % and -5% step changes in reference speed have been applied to test the performance of controller for set-point tracking control. The results are presented for both PID controller settings, on the same graphs for better comparison of

- Change in duty-ratio of buck-converter (Figure 9);
- Change in speed (Figure 10);
- Electromagnetic torque developed (Figure 11).
- Voltage input to armature (Figure 12).

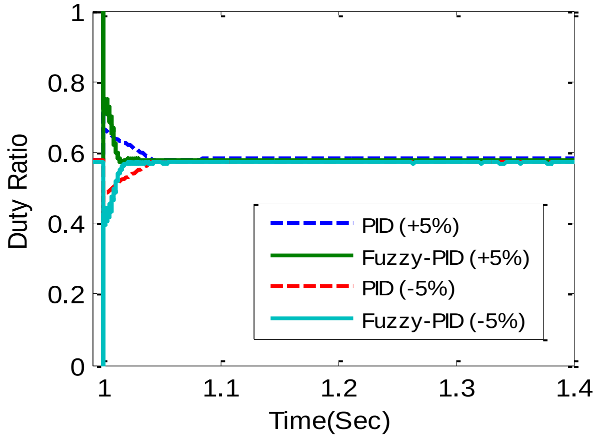

Figure 9. Adaptive Duty Ratio for Tracking Control

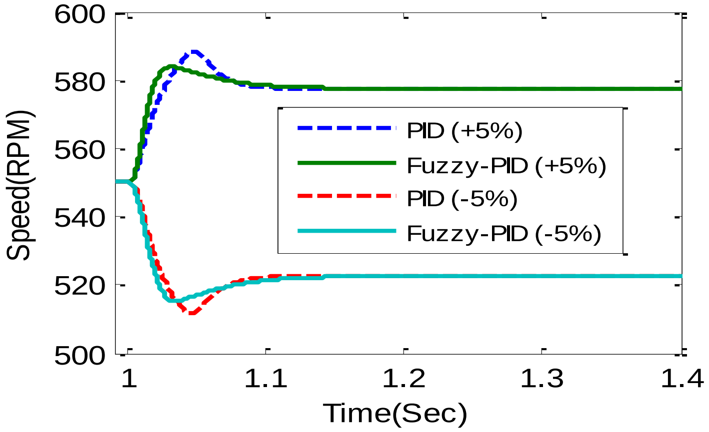

Figure 10. Motor Speed under Tracking Control

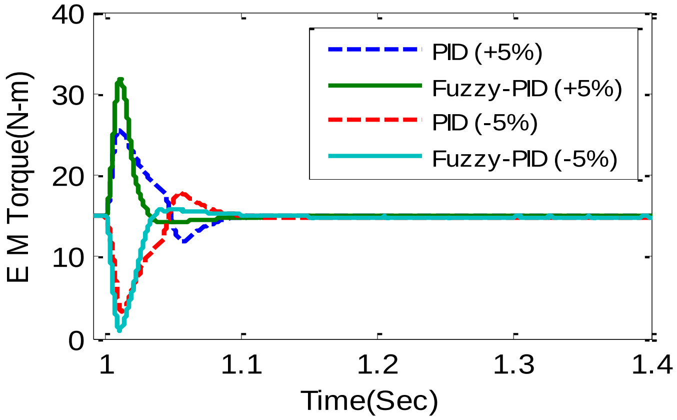

Figure 11. Electromagnetic Torque Developed under Tracking Control

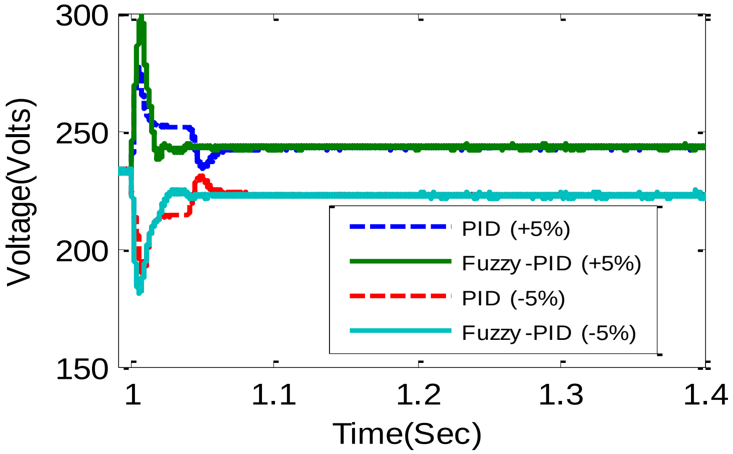

Figure 12. Motor Input Voltage for Tracking Control

For tracking control problem ±5% step change in reference is applied at 1 Sec. It is observed from the results for transients in speed, duty ratio of buck-converter, electromagnetic torque, input voltage as well as input power that fuzzy-PID controller results in smaller variations and tracking is achieved faster.

To present a quantitative comparison, the time- response specifications for case – 1 i.e. rise time, settling time, % overshoot and mean squared error are shown in Table 4.

Table 4. Performance for Set-point Tracking for + 5 % Change in Reference

Performance indicators	with ZN- based PID	with Fuzzy-PID	% improvement
Rise Time	0.0176	0.0143	18%
Settling Time	0.0623	0.0456	26%
% Overshoot	22.39	16.04	28%
MSE	0.4634	0.3415	26%

5.2. Disturbance Rejection Control

This is an important feature of any controlled system. To test for this feature, the machine was fully loaded at 0.5 sec at rated speed and then ±50% of full load step change has been applied at 1 sec. The results are presented for both cases of PID controller setting, on the same graphs for better comparison of

- Change in duty-ratio of buck-converter (Figure 13);
- Change in speed (Figure 14);
- Electromagnetic torque developed (Figure 15);
- Voltage input to armature (Figure 16).

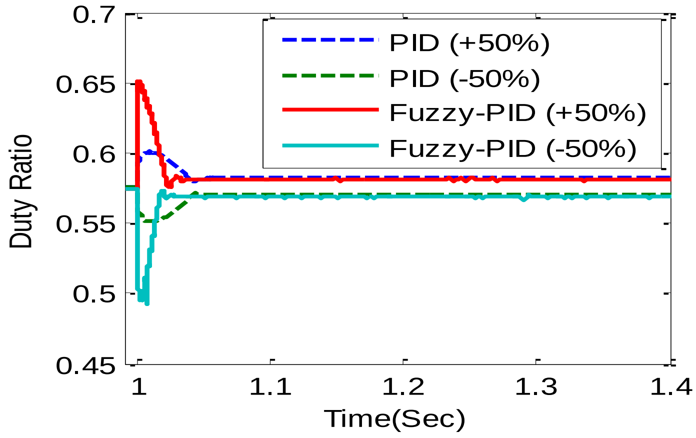

Figure 13. Adaptive Duty Ratio for Regulatory Control

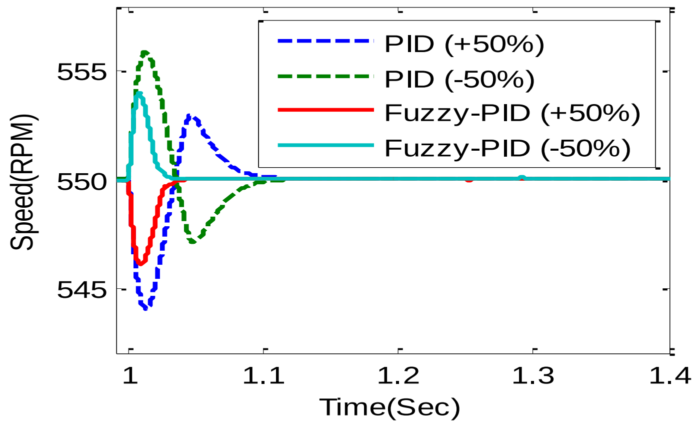

Figure 14. Motor Speed under Regulatory Control

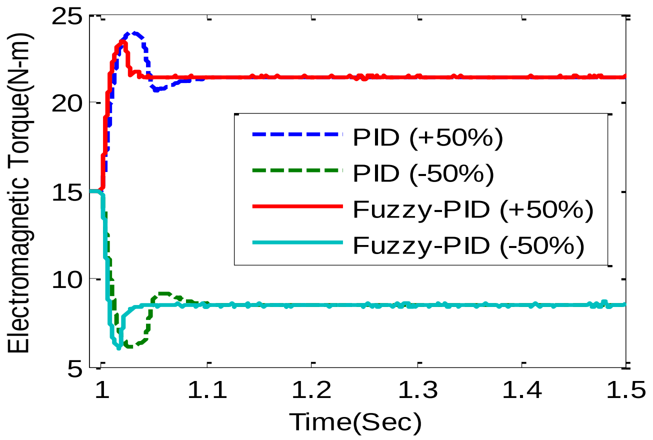

Figure 15. Torque Developed under Regulatory Control

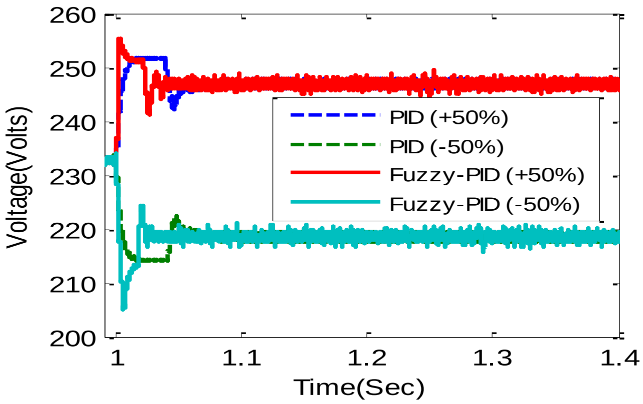

Figure 16. Motor Input Voltage for Regulatory Control

For regulatory control (load disturbance rejection control) ±50% step change in load is applied at 1 sec. It is observed from the above set of results that, for each performance variable fuzzy-PID approach provides a much improved performance. For the comparison of performance of the two controllers in case of the load disturbance rejection problem, the performance measures have been chosen to be – maximum change in speed in RPM and percent of normal, time taken by the drive to come back to normal speed, and mean square error, and presented in Table 5.

Table 5. Disturbance Rejection Performances with ±50% Load Change

Performance indicators	with ZN based PID	with Fuzzy-PID	% improvement
Max speed change (RPM) when disturbance applied	6.00	4.00	33%
Time taken to reject	0.04	0.03	25%
Max % deviation in speed due to load disturbance	1.1	0.72	34%
MSE	0.1180	0.0769	34%

Thus, the PID controller tuning by fuzzy approach as proposed in this paper shows improved results for load-disturbance rejection case also.

6. Conclusion

The results have been compared for both types of control problems that are encountered in drives control and the performance measures of the speed control of dc motor and have been included in Table-4 and Table-5. The tracking performance has been observed to improve up to 25% and disturbance rejection performance has improved up to 33%, with control effort well within the permissible limits. The controller is more robust with adaptation of fuzzy logic and gives better performance over conventional PID controller with non-linear buck converter included as final control element in place, as in the case of any real implementation.

It can be concluded that a dc drive with nonlinear buck-converter as the final control element, can be efficiently controlled with the proposed fuzzy logic-based PID controller working on case-based-rules developed. This improves the performance of the closed loop dc-drive system, compared to the conventional PID controller.

7. Nomenclature

D = duty ratio of the converter
V_d = converter input voltage
f = switching frequency of the converter
ΔI_L = peak to peak change in the inductor current
ΔV_c = peak to peak change in the capacitor voltage
C= capacitance of the capacitor used in the converter
L= inductance of the inductor used in the converter
A_1=system matrix when switch is ON
B_1= input matrix when switch is ON
C_1= output matrix when switch is ON
A_2= system matrix when switch is OFF
B_2= input matrix when switch is OFF
C_2= output matrix when switch is OFF
A= overall system matrix
B= overall input matrix
c= overall output matrix
x=state vector
y=output vector
J= moment of Inertia
B=coefficient of viscous friction
Ra=armature Resistance
La=armature circuit Inductance
v= motor voltage
T_L= load torque
φ= magnetic flux
T= electromagnetic torque
i_a= armature current
ω_m= motor speed
A'= no. of parallel paths
P= no. of poles
Z= no. of armature conductor

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