FUZZY LOGIC SPEED CONTROL OF A DC MOTOR

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Abstract— This paper presents a simulation of the speed control of a DC motor using Fuzzy Logic Control (FLC) at MATLAB environment. The Fuzzy Logic Controller designed in this study applies the required control voltage based on motor speed error *(e)* and its change *(ce)*. The performance of the driver system was evaluated through digital simulations using Simulink toolbox of Matlab®. The simulation results show that the control with FLC outperforms PI control in terms of overshoot and steady state error.

Keywords- DC motor; Fuzzy Logic; Speed Control

I. INTRODUCTION

The speed of DC motors can be adjusted within wide boundaries so that this provides easy controllability and high performance. DC motors used in many applications such as still rolling mills, electric trains, electric vehicles, electric cranes and robotic manipulators require speed controllers to perform their tasks. Speed controller of DC motors is carried out by 'means of voltage control in 1981 firstly by Ward Leonard [1]. The regulated voltage sources used for DC motor speed control have gained more importance after the introduction of thyristor as switching devices in power electronics. Then semiconductor components such as MOSFET, IGBT and GTO have been used as electric switching devices [2].

In general, the control of systems is difficult and mathematically tedious due to their high nonlinearity properties. To overcome this difficulty, FLC can be developed. The best applications of FLC are the time-variant systems that are nonlinear and ill-defined [3]. One of the most important FLC applications in real life is the metro system in the city Sendia of Japan in 1987 [4]. Nowadays, FLC applications are successfully used in many fields including automatic focus cameras, household materials such as dishwashers, automobile industry etc.

In this study, the speed response of a DC motor exposed to fixed armature voltage was investigated for both under loaded and unloaded operating conditions. The first, the DC motor was operated for a required reference speed under loaded and unloaded operating conditions using PI control method. Then, to make performance comparison, the speed of the system was controlled using FLC. The FLC system designed for operating at fixed speed under different load conditions

are simulated at MATLAB/Simulink environment. In this study, we used a chopper circuit as a motor driver.

II. MOTOR MODEL

The resistance of the field winding and its inductance of the motor used in this study are represented by R_f and L_f, respectively. The resistance of the armature and its inductance are shown by R_a and L_a respectively in dynamic model. Armature reactions effects are ignored in the description of the motor. This negligence is justifiable to minimize the effects of armature reaction since the motor used has either interpoles or compensating winding. The fixed voltage V_f is applied to the field and the field current settles down to a constant value.

A linear model of a simple DC motor consists of a mechanical equation and electrical equation as determined in the following equations:

$$J_m \frac{d\omega_m}{dt} = K_m.\phi.I_a - b.\omega_m - M_{load} \qquad (1)$$

$$L_a \frac{dI_a}{dt} = V_a - R_a.I_a - K_b.\phi.\omega_m \qquad (2)$$

The dynamic model of the system is formed using these differential equations and Matlab Simulink blocks as shown in Fig. 1.
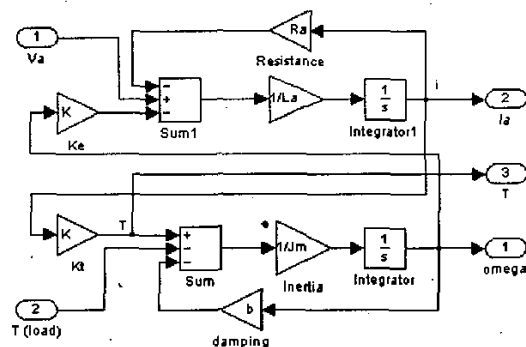

Figure 1. Matlab/Simulink model of DC motor

In this study, the parameters of DC motor are presented on Table 1.

TABLE I. DC MOTOR PARAMETERS

Parameters	Description	Value
Ra	Armature Resistance (Ω)	0.5
La	Armature Enductance (H)	0.003
Jm	Motor of Inertia (kg.m^2/s^2)	0.0167
K = K_e ($K_b.\phi$) = K_t ($K.\phi$)	Motor Constant (Nm/Amp)	0.8
b	Damping ratio of mechanical system (Nms)	0.0167

III. FUZZY LOGIC CONTROLLER (FLC) DESCRIPTION AND DESIGN

The fuzzy logic foundation is based on the simulation of people's opinions and perceptions to control any system. One of the methods to simplify complex systems is to tolerate to imprecision, vagueness and uncertainty up to some extent [5]. An expert operator develops flexible control mechanism using words like "suitable, not very suitable, high, little high, much and far too much" that are frequently used words in people's life. Fuzzy logic control is constructed on these logical relationships. Fuzzy sets are used to show linguistic variables. Fuzzy Sets Theory is first introduced in 1965 by Zadeh to express and process fuzzy knowledge [6, 7]. There is a strong relationship between fuzzy logic and fuzzy set theory that is similar relationship between Boolean logic and classic set theory. Fig. 2 shows a basic FLC structure.
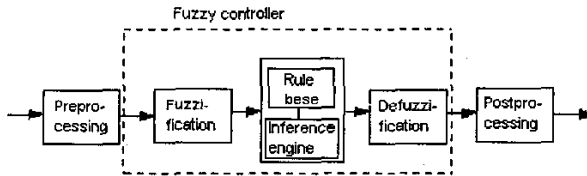

Figure 2. Process Blocks for a Fuzzy Controller

Although the classic controllers depend on the accuracy of the system model and parameters, FLC uses different strategies for motor speed control. Basically, FLC process is based on experiences and linguistic definitions instead of system model. It is not required to know exact system model to design FLC. In addition to this, if there is not enough knowledge about control process, FLC may not give satisfactory results [8].

A. Defining inputs, outputs and universe of discourse:

The goal of designed FLC in this study is to minimize speed error. The bigger speed error the bigger controller input is expected. In addition, the change of error plays an important role to define controller input. Consequently FLC uses error *(e)* and change of error *(ce)* for linguistic variables which are generated from the control rules. Equation (3) determines required system equations. The output variable is the change in control variable *(ca)* of motor driver. *ca* is integrated to achieve desired alpha value. Here α is a angular value determining duty cycle of DC-DC converter designed in this paper.

$$e(k) = [w_r(k) - w_a(k)] \times K1_E$$
$$ce(k) = [e(k) - e(k-1)] \times K2_{CE} \qquad (3)$$
$$ca(k) = [\alpha(k) - \alpha(k-1)] \times K3_{Ca}$$

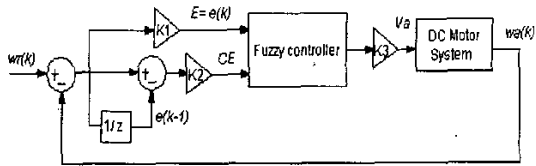Here $K1_E$, $K2_{CE}$ and $K3_{Ca}$ are each gain coefficients and *k* is a time index.

Figure 3. Block diagram of the DC motor control

The error *(e)* approaches to its smallest value when the motor speed is attained to nominal value. If we reverse this value, the error interval can be defined between −200 and 200.

When the simulation of system was performed at unloaded condition, the change of error is shown in Figure 4. In this figure, the change of error can be seen between −1.6 and 0.1 intervals. Then this change was optimized between −1 and 1 in the membership functions.
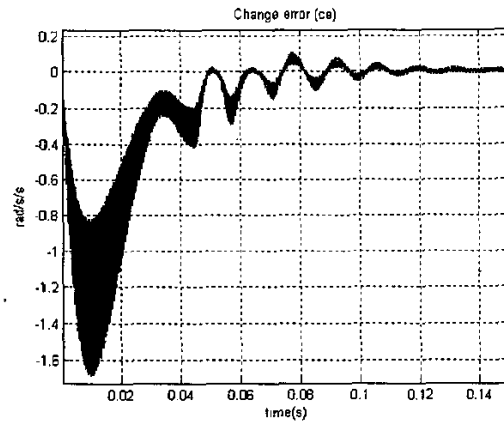

Figure 4. Change of Error

In order to optimize the speed control, the intervals of membership functions are found after some manual changes as follows:

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$$e\omega : -150 \quad \text{and} \quad +150 rad/s$$
$$ce\omega : -1 \quad \text{and} \quad +1\, rad/s/s \tag{4}$$
$$c\alpha = 150.10^3 \quad \text{and} \quad -150.10^3$$

The gain values are determined for these intervals in simulation model as $K1_E = 1/150$, $K2_{CE} = 1$ and $K3_{C\alpha} = 150 \times 10^3$.

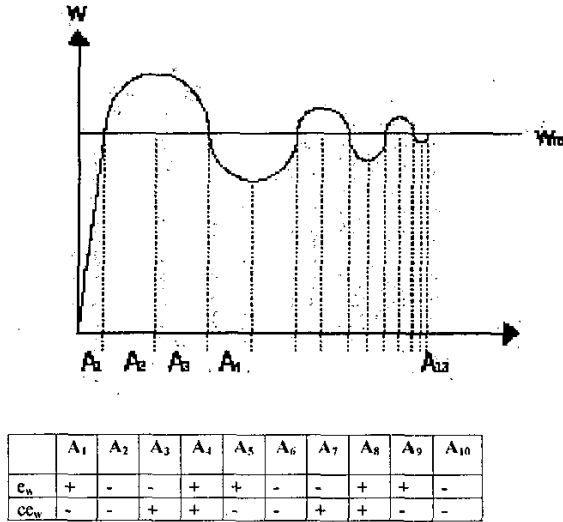|	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
e_w	+	-	-	+	+	-	-	+	+	-
ce_w	-	-	+	+	-	-	+	+	-	-

Figure 5. Dynamic Signal Analysis

Where A_1, A_2, ...An represent reference intervals.

B. Defining membership functions and rules:

System speed comes to reference value by means of the defined rules. For example, first rule on Table 2 determines, 'if (e) is NL and (ce) is NL than (c_α) is PL' According to this rule, if error value is negative large and change of error value is negative large than output, change of alpha will be positive large. In this condition, corresponding A_2 interval in Fig. 5, motor speed is larger than reference speed and still wants to increase strongly. This is one of the worst conditions in control process. Because of the fact that alpha is smaller than the required value, its value can be increased by giving output PL value. This state corresponds to motor voltage decreasing. All conditions in control process are shown in Fig. 5.
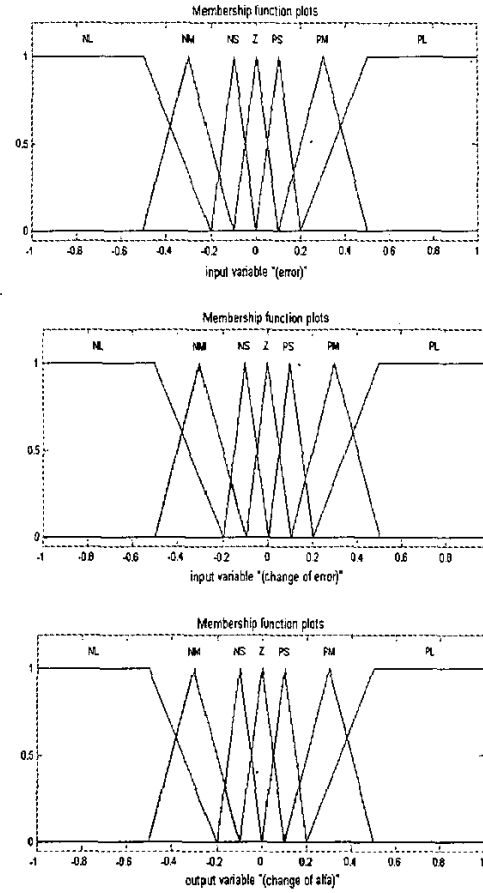
Figure 6. Linguistic rules for angle (α) determination for driver circuit. a) speed error b) change of speed error c) change of alfa

To be calculated FLC output value, the inputs and outputs must be converted from 'crisp' value into linguistic form. Fuzzy membership functions are used to perform this conversion. In this paper, all membership functions are defined between -1 and 1 interval by means of input scaling factors $K1_E$ and $K2_{CE}$, and output scaling factor $K3_{C\alpha}$. Thus, since simple numbers are now processed in controller after scaling, fuzzy computation is performed in a shorter time. The linguistic terms for input and output values are represented by seven membership functions as shown in Fig. 6.

TABLE II.   THE RULE DATA BASE

ce \ e	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PL	PL	NM	Z	Z
NM	PL	PL	PL	PM	PS	Z	Z
NS	PL	PM	PS	PS	PS	Z	Z
Z	PL	PM	PS	Z	NS	NM	NL
PS	Z	Z	NM	NS	NS	NM	NL
PM	Z	Z	NS	NM	NL	NL	NL
PL	Z	Z	NM	NL	NL	NL	NL

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IV. SIMULATION

A. Driver circuit and modelling

DC choppers used as a driver in this work change the average value of load voltage applied from a fixed DC source by switching a power switch such as tyristor, BJT. With wide usage ranges in power electronic, separately excited and serial DC motor speed control can be mentioned as the most important application area of DC choppers.
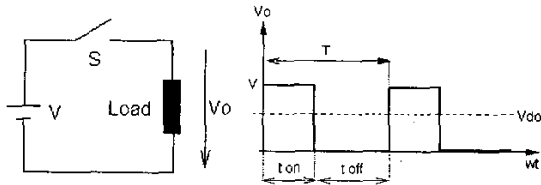

Figure 7. Operating prenciple and output waveform of Driver

Using Fig. 7, the average output voltage can be calculated as

$$V_{do} = \frac{t_{on}}{t_{on} + t_{off}} . V \qquad (5)$$

where V is the DC source voltage. V_{do} can be controlled using three methods :

- Hold t_{off} fixed and change t_{on} (frequency modulation)

- Hold period $(t_{on} + t_{off})$ fixed and change t_{off} / t_{on} rate (pulse width modulation)

- Change t_{off} and t_{on} separately. (Combination of first and second method)

In this paper, one-quadrant DC chopper is designed as a driver. In one-quadrant driver, load voltage and load current can take only positive values. If load inductance is too small to provide continuous current, discontinuous current operating condition is present. Simple power circuit of a one-quadrant DC chopper and general waveforms for continuous current condition are shown in Fig. 8 and Fig. 9, respectively.
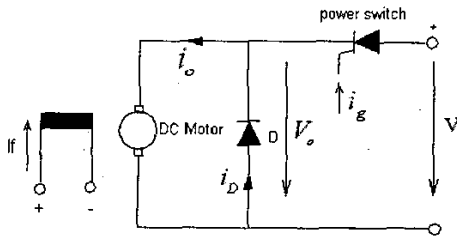

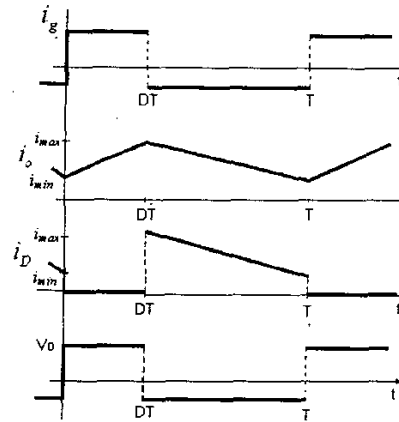Figure 8. Simple power circuit of a one-quadrant DC chopper

Figure 9. General waveforms for continuous current condition

DC chopper model used in simulation model is shown in Fig. 10. To control average output voltage, V_{do}, pulse width modulation (PWM) technique is used.
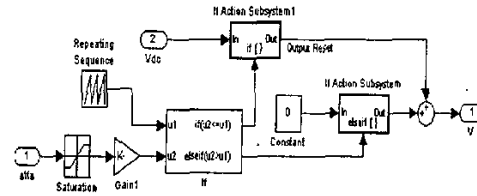

Figure 10. DC Chopper Model

Fundamentally, the operating principle of driver model is based on the comparison of two signals [9]. One of the signals is a triangular waveform which represents one period of 2 KHz chopping frequency and other one is fixed linear signal which represents time equivalent of alpha trigging angle (t_α). Since chopping frequency is 2 KHz, the amplitude of triangular waveform starts from zero and reaches $1/2.10^3 = 0.0005$ value. On the other hand, the alpha signal from controller is multiplied by $0.0005/360$ value to calculate the time corresponding to this angle. Alpha time signal and triangular signal are U_1 and U_2 variables of 'IF' block used in simulation model shown in Fig. 10, respectively.
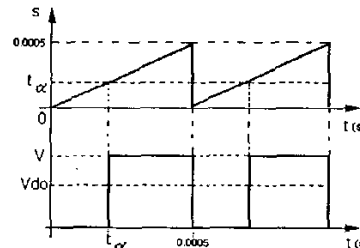

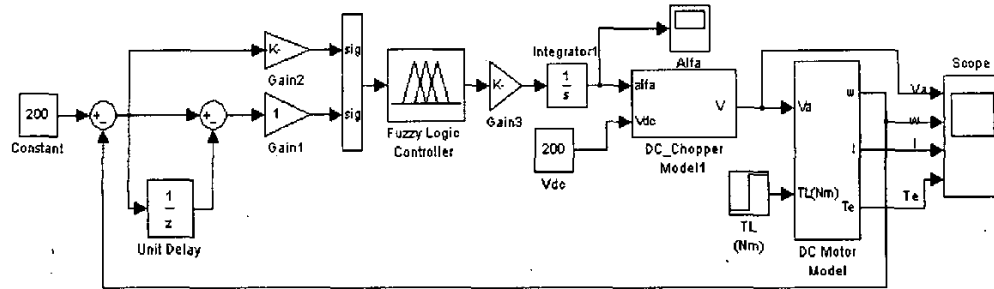Figure 11. Input and output signals of driver model

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V. CONTROL SIMULATION

Figure 12. FLC Simulink Model

(a)

(b)

(c)

(d)

(e)

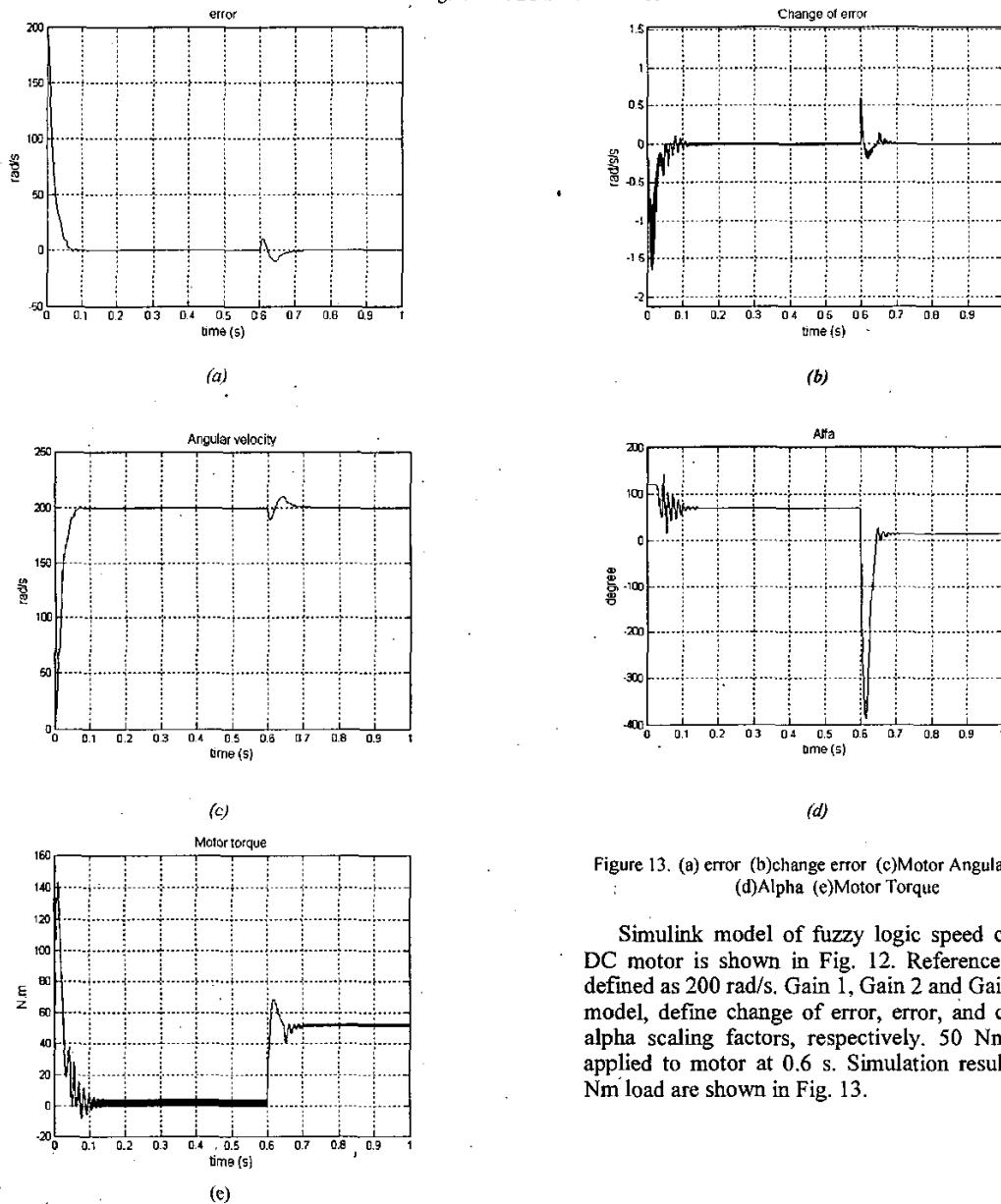Figure 13. (a) error (b)change error (c)Motor Angular Velocity (d)Alpha (e)Motor Torque

Simulink model of fuzzy logic speed control of DC motor is shown in Fig. 12. Reference speed is defined as 200 rad/s. Gain 1, Gain 2 and Gain 3 in the model, define change of error, error, and change of alpha scaling factors, respectively. 50 Nm load is applied to motor at 0.6 s. Simulation results for 50 Nm load are shown in Fig. 13.

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TABLE III. PERFORMANCE ANALYSIS OF CONTROLLERS

Load		10N	30N	50N
P I	C_1 %M_p	5.955	5.045	5.527
	e_{ss}	-0.393	-0.288	-0.191
	C_2 %M_p	5.635	5.6315	5.632
	e_{ss}	-0.25	-0.195	-0.15
	C_3 %M_p	5.7315	5.7315	5.7315
	e_{ss}	-0.18	-0.15	-0.12
	C_4 %M_p	5.895	5.895	5.895
	e_{ss}	-0.1175	-0.09	-0.075
FLC	%M_p	0.81	2.04	4.93
	e_{ss}	0.0062	-0.0045	-0.018

(a) For different loads

The controller designed has been simulated for 10, 30 and 50 Nm load values; then percent overshoot (%M_p) and steady state error (e_{ss}) have been measured. PI controller responses for different Kp Ki coefficients and FLC responses are compared on Table 3. As seen from the table, FLC outperforms PI controller in terms of overshoot and steady state error criteria.

VI. CONCLUSIONS

Separately excited DC motor speed control has been performed in Matlab Simulink environment. DC motor speed has been controlled with classical PI Controller and Fuzzy Logic Controller (FLC). In this paper, it is also designed a circuit model as a driver to get more reasonable results.

Simulation results show that FLC has clearly better performance for providing T_r (rise time), e_{ss} (steady state error) and %M_p (percent overshoot) criteria in comparison with PI controller. FLC also has more sensitive responses against load disturbances in according to classical PI controller.

It would be possible to get better PI controller performances by increasing K_p and K_i coefficients. But, in this case, it will be a problem in real application of PI controller.

Criter	PI				FLC
	C_1	C_2	C_3	C_4	
T_r	0.141	0.141	0.141	0.141	0.036
e_{ss}	-0.933	-0.579*	-0.415	-0.262	-0.01
%M_p	5.527	5.631	5.731	5.894	0.68

b) Unloaded operation

C_1: K_p=100, K_i=15 T_r: Rise Time (s)
C_2: K_p=200, K_i=25 e_{ss}: Steady State Error (rad/s)
C_3: K_p=300, K_i=28 %M_p: Percent overshoot
C_4: K_p=500, K_i=30 C_1..C_4:Different
 K_p&K_i coefficients

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