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Design and Tuning of P, I, D Group Controllers for Position Control of BLDC Motor Drive System

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Abstract
This paper presents the position control of BLDC motor with P, PI, PD, PID controllers. Hear we derive the Transfer function model for the position control of the BLDC motor. For the transfer function model of the BLDC motor the P, PI, PD, PID Controllers are tuned by two methods, they are Ziegler-Nichols method and Tyrues-luyben method. Here we compare the performance specifications such as Rise time, Peak time, %overshoot, Settling time and Steady state error for different controllers to analysis the system performance and we also compare the Gain margin, phase margin, Gain cross over frequency and phase cross over frequency for analyzing the stability of the system.

Index Terms— ***Brush Less DC (BLDC) motor, Proportional controller, Proportional Integral controller (PI), Proportional Derivative controller (PD), Proportional Integral Derivative controller (PID), Rise time, Peak time, %overshoot, Settling time,Steady state error, Gain margin, phase margin, Gain crossover frequency, Phase crossover frequency, Ziegler-Nichols method, Tyrues-Luyben method***

INTRODUCTION

THE BLDC motors are one of the motor types that have TmoreTHE rapidly gain popularity, mainly because of their better characteristics and performance. These motors greatly used in industrial sectors because of its characteristics like high efficiency, silent operation, reliability, compact form, and low maintenance.

In a conventional (brushed) DC motor, the brushes make mechanical contact with a set of electrical constants on the rotor (called commentator), forming an electrical circuit between the DC electrical source and the armature coil windings. As the armature rotates on axis, the stationary brushes come in contact with different sections of rotating commutator. The commutator and brush system forms electrical switches,

In a BLDC motor, the electromagnets do not move, instead, the permanent magnets rotate and the armature is stationary. This gets a problem of how to transfer current to a moving armature. In order to do this, the commutator assembly is replaced by intelligent electronic controller. The controller performs the same power-distribution found in a brushed motor, but using a solid state circuit rather than a commutator.

BLDC motor find applications in every segment of the market such as applications, industrial control, automation, aviation so on. The BLDC motor control is categorized in to three major types such as constant load, varying load, positioning applications.
BLDC motors with constant loads are used in applications where variable speed is more important than the accuracy of the speed. In these types of applications the load is directly coupled to the motor shaft. For example fans, blowers, pumps come under these types of applications.

BLDC motor with varying loads is used in applications where the load on the motors varies over a speed range.

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Washers, dryers and compressors are good examples as home applications.

BLDC motors with position applications are used in most of the industrial and automation types of applications. The applications in this category have same kind of power transmission, which could be mechanical gears or timer belts or a simple belt driven systems.

MODELING OF BLDC MOTOR

Transfer Function of BLDC motor

In this section we discuss the transfer function model of BLDC motor by taking the DC motor as reference, so first we represent the mathematical modal of DC motor from that BLDC motor transfer function is obtained

A typical dc motor equivalent circuit is illustrated as shown in the circuit shown below in fig 1 and fig 2

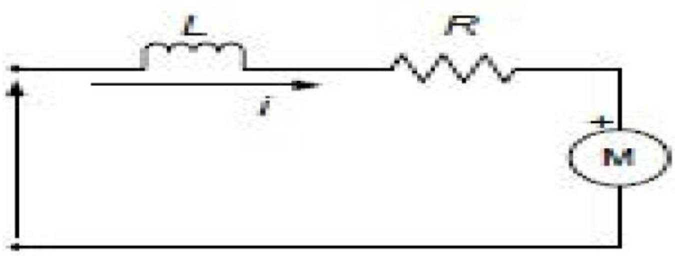

Fig 2.1 A typical DC motor equivalent electrical circuit

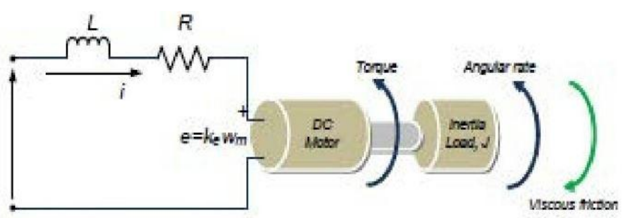

Fig 2.2 A typical DC motor electromechanical system arrangement

Applying Kirchhoff's Voltage Law to fig 1, KVL, the following equation 1 is obtained:

$$V_s = Ri + L\frac{di}{dt} + e \qquad (1)$$

Apply Laplace transform,

$$V_s(s) = RI(s) + LsI(s) + E(S) \qquad (2)$$

Applying Kirchhoff's Voltage Law to fig 1, KVL, the following equation 3 is obtained

$$T_e = K_f\omega_m + J\frac{d\omega_m}{dt} + T_L \qquad (3)$$

Apply Laplace transform to (3) assume load torque is zero,

$$T_e(s) = K_f\omega_m(s) + Js\omega_m(s) \qquad (4)$$

Where

Te=the electrical torque

K_f=the friction constant

J=the rotor inertia

W_m=the angular velocity

TL=the supposed mechanical load.

Where the electrical torque and the back emf could be written as

$$e = K_e\omega_m \text{ and } Te = K_t i \qquad (5)$$

Where,

K_e=the back emf constant

K_t=the torque constant

The transfer function is therefore obtained as follows using the ratio of and the angular velocity, ω_m to source voltage, V_s.

That is,

$$G(s) = \frac{\omega_m}{V_s} = \frac{K_t}{s^2JL + sK_fL + sRJ + K_fR + K_eK_t} \qquad (6)$$

From these, the transfer function could be derived accordingly as follows;

That is

$$G(s) = \frac{\omega_m}{V_s} = \frac{K_t}{s^2JL + s(K_fL + RJ) + K_fR + K_eK_t} \qquad (7)$$

Considering the following assumptions;

1. The friction constant is small, that is, K_f tends to 0, this implies that;
2. RJ>> K_f L, and
3. K_eK_t >>R K_f

And the negligible values zeroed, rearranging variables the transfer function is finally written as

$$G(s) = \frac{\omega_m}{V_s} = \frac{K_t}{\frac{RJ}{K_eK_t} * \frac{L}{R}s^2 + s\frac{RJ}{K_eK_t} + 1} \qquad (8)$$

Mathematical model of a typical BLDC motor

Typically, the mathematical model of a brushless dc motor is not totally different from the conventional DC motor. The major thing addition is phases involved which affect the overall results of the BLDC model. The phases peculiarly affect the resistive and the inductive of the BLDC arrangement. For example, a simple arrangement with a symmetrical 3-phase and "WYE" internal connection could give a brief illustration of the whole phase concept.

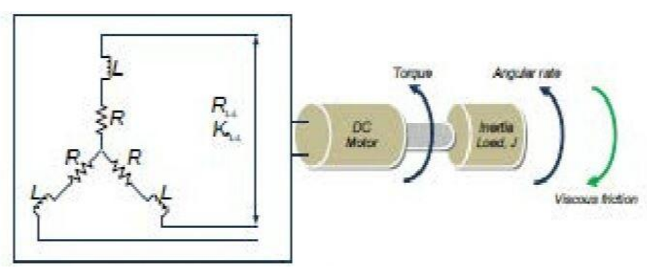

Fig 2.3 Brushless dc motor schematic diagram

The difference will affect primarily the mechanical and electrical constants as they are very important parts of modeling parameters.

For the mechanical time constant (with symmetrical arrangement),

$$\tau_m = \sum \frac{RJ}{K_e K_t} = \frac{J\sum R}{K_e K_t} \qquad (9)$$

The electrical (time constant),

$$\tau_e = \sum \frac{L}{R} = \frac{L}{\sum R} \qquad (10)$$

Therefore, since there is a symmetrical arrangement and a there phase, the mechanical and electrical constants becomes;

Mechanical constants

$$\tau_m = \frac{J3R}{K_e K_t} \qquad (11)$$

Electrical constants

$$\tau_e = \frac{L}{3R} \qquad (12)$$

Considering the phase effects,

$$\tau_m = \frac{3R_\phi J}{\frac{K_{e(L-L)}}{\sqrt{3}} K_t} \qquad (13)$$

Equation 4.5 becomes;

$$\tau_m = \frac{3R_\phi J}{K_e K_t} \qquad (14)$$

Where K_e is the phase value of the EMF (voltage) Constant

$$K_e = \frac{K_{e(L-L)}}{\sqrt{3}}$$

Also there is a relationship between K_e and K_t; using the electrical power (left hand side) and mechanical power (right hand side) equations; that is

$$\sqrt{3} \times E \times I = \frac{2\pi}{60} \times N \times T$$

$$\frac{E}{N} = \frac{T}{I} \times \frac{2\pi \times 1}{60 \times \sqrt{3}}$$

$$K_e = K_t \times \frac{2\pi \times 1}{60 \times \sqrt{3}}$$

$$K_e = K_t \times 0.0605$$

Where,

$K_e = \left[\frac{\text{v-secs}}{\text{rad}}\right]$; The electrical torque

$K_t = \left[\frac{N-M}{A}\right]$; The torque constant

Therefore, the equation for the BLDC can now be obtained as follow from equation by considering the effects of the constants and the phase accordingly.

$$G(s) = \frac{W_m(s)}{V(s)} = \frac{\frac{1}{K_e}}{\tau_m \tau_e s^2 + \tau_m s + 1} \qquad (15)$$

$$\frac{W(s)}{V(s)} = \frac{\frac{1}{K_e}}{\frac{RJ}{K_e K_t}\frac{L}{R}s^2 + \frac{3RJ}{K_e K_t}s + 1} \qquad (16)$$

Above equation represents the relation between the angular speed and supply voltage, to get position we should integrate the angular speed of the motor

$$\theta(s) = \frac{1}{s} W(s)$$

Where 1/s represents integration in frequency domain

Therefore the transfer function becomes

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$$\frac{\theta(s)}{V(s)} = \frac{\frac{1}{K_e}}{s(\frac{RJ\quad L}{K_eK_tR}s^2+\frac{3RJ}{K_eK_t}s+1)} \quad (17)$$

CONTROLLERS AND THEIR TUNING

Proportional controller

Proportional controller produces an output which is proportional to error signal.

$$u(t)\ \alpha\ e(t)$$
$$u(t) = K_p e(t)$$

Therefore, the transfer function of the Proportional controller is K_p

K_p is proportionality constant and gain of the controller

The proportional controller used to change the transient response as per the requirement

Proportional derivative controller

The Proportional Derivative controller produces an output which is the combination of outputs of Proportional and

Derivative controller.

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt}$$

The proportional derivative controller is used to improve the stability of the control system without affecting the steady state error.

Proportional Integral (PI) Controller

Proportional Integral controller produces an output which is combination output of proportional integral controllers.

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

Proportional integral controller is used to decrease the steady state error without affecting the stability of the control system.

Proportional Integral Derivative (PID) Controller

Proportional Integral controller produces an output which is combination output of proportional integral controllers.

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int e(t)dt$$

Proportional integral derivative controller is used to improve the stability of control system and to decrease the steady state error.

Controller tuning methods

In this section we discuss the controller tuning methods Ziegler Nichols method and Tyrues-Luyben method. Tuning is the procedure of finding the values of K_p, K_i, K_d.

Ziegler-Nichols method

PID controller for position control of BLDC motor by Zeigler-Nichols method to select the K_p, K_i, K_d the following steps are required.

Step1: Apply a finite value to the proportional gain.

Step2: Make the integral time to very high value (i.e. infinity) and the derivative time to zero.

Step3: Apply step input to the system

Step4: Keep changing the proportional gain value until we get the oscillatory response with constant amplitude.

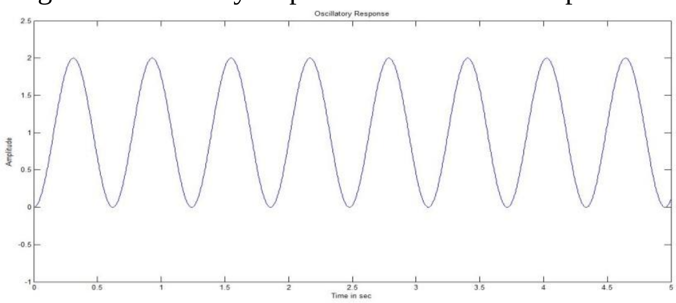

Fig 3.1 Oscillatory response curve for gain Ku

From the above figure we can get the gain K_u and the time t_u period for the controller settings

Rules for different Controller settings by Ziegler-Nichols tuning rules are shown in below table

Table 3.1 Ziegler-Nichols tuning table

Type of controller	K_p	T_i	T_d
P	$0.5K_u$	∞	0
PI	$0.45 K_u$	$\frac{t_u}{1.2}$	0
PID	$0.6K_u$	$0.5t_u$	$0.125t_u$

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Tureus-Lyuben method

The Tyreus-Luyben tuning procedure is quite similar to Ziegler Nichols tuning procedure. But controller settings are different. The settings that are based on the gain (Ku) and time period (t_u) are shown in the table below.

Table 3.2 Tyreus-Luyben tuning rules for different controllers

Controller	Kp	Ti	Td
PI	0.3125Ku	$2.2t_u$	-
PID	0.3125Ku	$2.2t_u$	$0.152t_u$

Where K_u and t_u are calculated from oscillatory response curve mentioned above.

$$G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d s)$$

DESIGN OF CONTROLLER FOR POSITION CONTROL OF BLDC MOTOR AND SIMULATIONS

The BLDC motor has parameters for both stator and rotor. The parameters are stator phase resistance, stator phase inductance, inertia, back emf constant, friction coefficient, torque constant, number of poles. For a particular BLDC motor the parameters considered as shown in table below.

Table 4.1.Parameters of BLDC motor

R	Stator phase resistance	2.875 ohms
L	Stator phase inductance	8.5mH
J	Inertia	0.8 kg m^2
Ke	Back emf constant	0.5
B	Friction coefficient	0.001
Kt	Torque constant	1.4
P	Number of poles	4

By subtitling the parameters in the table in transfer function equation 17, we get the transfer function of the BLDC as

$$\frac{\theta(s)}{V(s)} = \frac{2}{s(0.0097s^2 + 9.875s + 1)} \quad (18)$$

The block diagram of above transfer function is

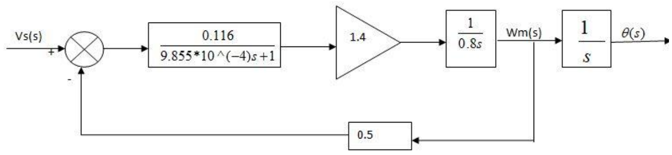

Fig 4.1.Block diagram model BLDC motor

Applying step input to the block diagram in figure 4.1, the response is obtained as follows

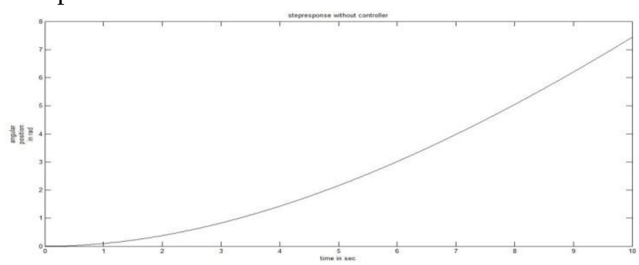

Fig 4.2.Step response for position control BLDC motor

4.1 Ziegler-Nichols method

Since the step response of the position controlled BLDC is a exponentially increasing that means the system is unstable. So a controller has to be designed in order to make the system stable. PID controller for position control of BLDC motor by Zeigler-Nichols method to select the K_p, K_i, K_d the following steps are required.

Step1: Apply a finite value to the proportional gain.

Step2: Make the integral time to very high value (i.e. infinity) and the derivative time to zero.

Step3: Apply step input to the system

Step4: Keep changing the proportional gain value until we get the oscillatory response with constant amplitude as follows

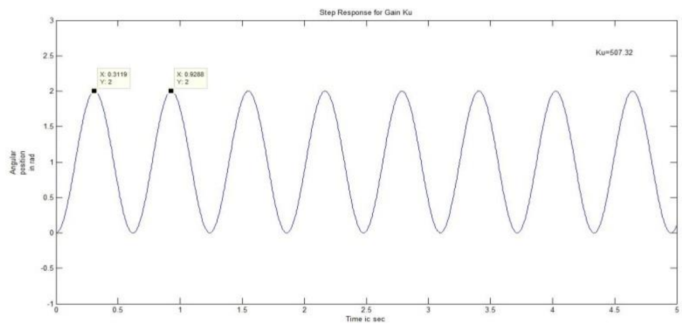

Fig 4.3.Oscillatory response curve

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We get the oscillatory response at Kp =507.32
Therefore the gain Ku=507.32 and from the graph period of oscillation t_u =0.6169

4.1.1. Proportional controller (P controller)

By Zeigler-Nichols tuning rules,

$$K_p = 0.6K_u \Rightarrow K_P = 0.6 * 507.32 \Rightarrow K_p = 304.392$$

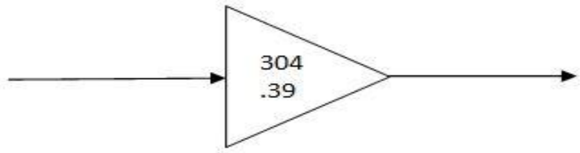

Fig 4.4.Proportional controller

Apply step input to the BLDC motor with proportional controller the response will be as shown in figure 4.10.

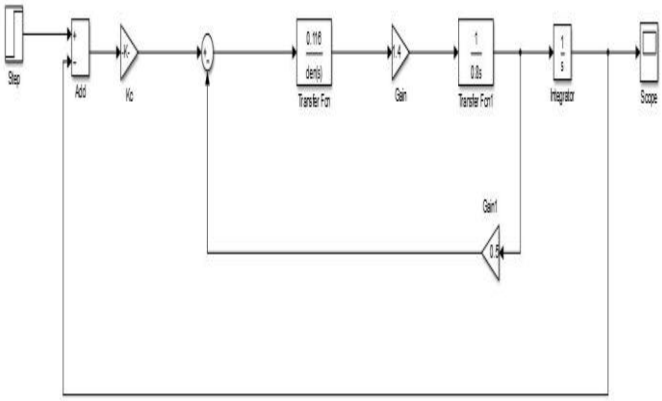

Fig 4.5.Simulation diagram of BLDC with P Controller

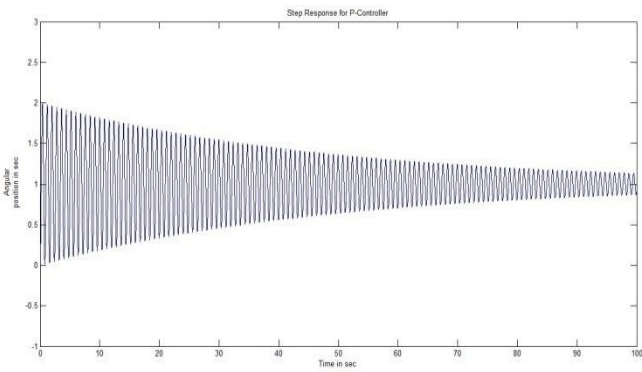

Fig 4.6.Step response of position control of BLDC motor with P-controller

The Bode plot for position control of BLDC motor with Proportional controller is shown and Figure 4.7

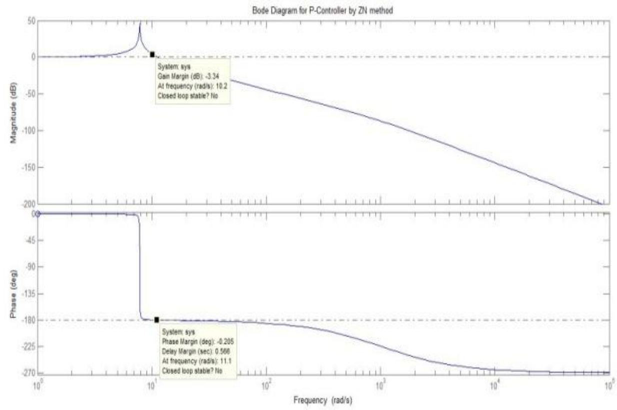

Fig 4.8.Bodeplot for position control of BLDC motor with Proportional controller

4.1.3 PI controller

By Zeigler-Nichols tuning rules,

$$K_p = 0.6 * K_u \Rightarrow K_p = 0.6 * 507.32 \Rightarrow K_p = 304.392$$

$$T_i = 0.5t_u \Rightarrow T_i = 0.5 * 0.6169 \Rightarrow T_i = 0.3085$$

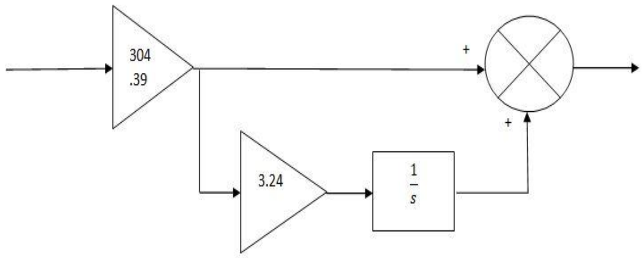

Fig 4.9.PI controller

Apply step input to BLDC motor with PI-Controller, The response is as shown in figure 4.10

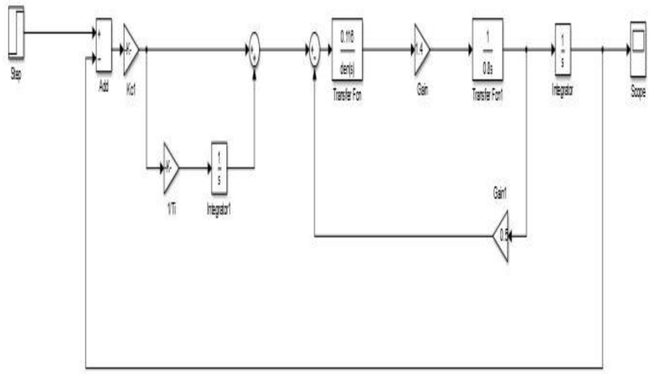

Fig 4.10.Simulation diagram of BLDC motor with PI Controller

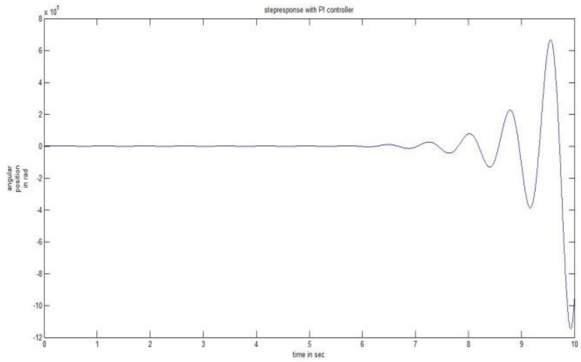

Fig 4.11.Step response of BLDC with PI controller

Bode plot for position control of BLDC motor with PI controller are shown and Figure 4.12

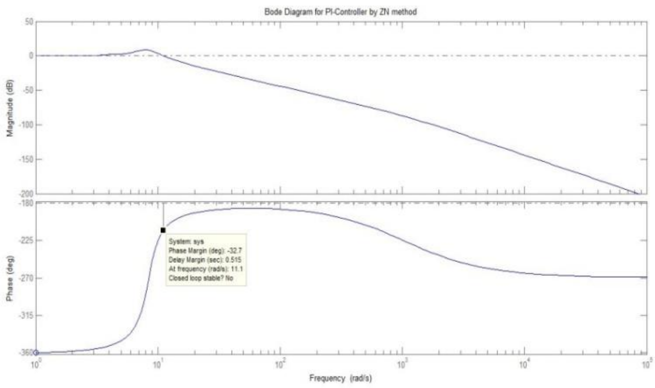

Fig 4.12.Bodeplot for position control of BLDC motor with PI Controller

4.1.3 PD controller

By Zeigler-Nichols tuning rules,

$$K_p = 0.6 * K_u \Rightarrow K_p = 0.6 * 507.32 \Rightarrow K_p = 304.392$$

$$T_d = 0.125 t_u \Rightarrow T_d = 0.125 * 0.6169 \Rightarrow T_d = 0.0771$$

The transfer function of PD controller is

$$G_c(s) = 304.39(1 + 0.0071s)$$

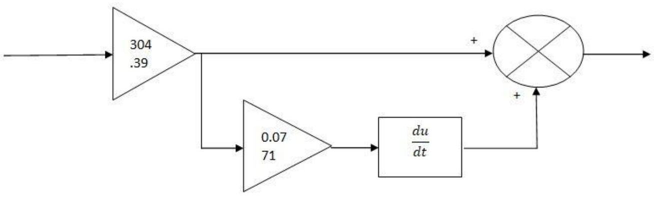

Fig 4.13.PD controller

Apply step input to the BLDC motor with PD controller, the response is shown in figure 4.14

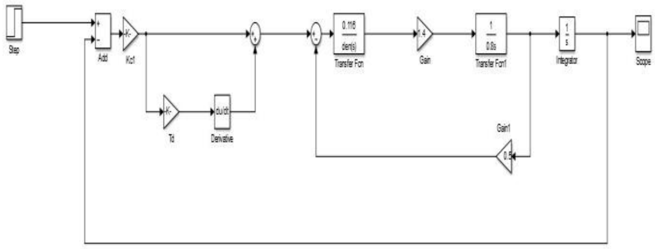

Fig 4.14.Simulation diagram of BLDC motor with PD Controller

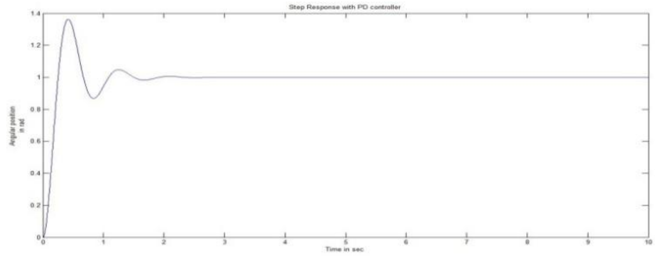

Fig 4.15.Step response of BLDC motor with PD controller

Bode plot for position control of BLDC motor with PD controller are shown Figure 4.16

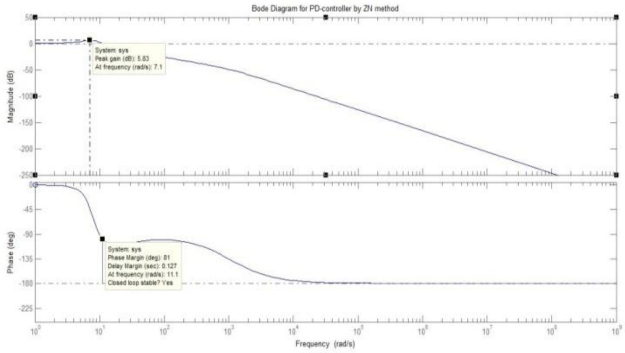

Fig 4.16.Bodeplot for position control of BLDC motor with PD Controller

4.1.4 PID controller

$$K_p = 0.6 * K_u \Rightarrow K_p = 0.6 * 507.32 \Rightarrow K_p = 304.392$$

$$T_i = 0.5 t_u \Rightarrow T_i = 0.5 * 0.6169 \Rightarrow T_i = 0.3085$$

$$T_d = 0.125 t_u \Rightarrow T_d = 0.125 * 0.6169 \Rightarrow T_d = 0.0771$$

The transfer function of controller is

$$G_c(s) = 304.39(1 + \frac{1}{0.3085s} + 0.0771s)$$

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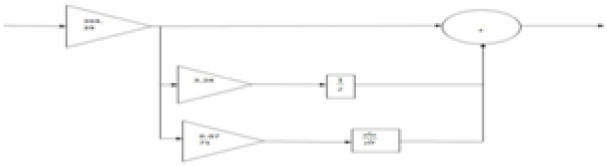

Fig 4.17.PID controller block diagram

Apply step input to the to BLDC motor with PI-Controller the response is shown in figure 4.19

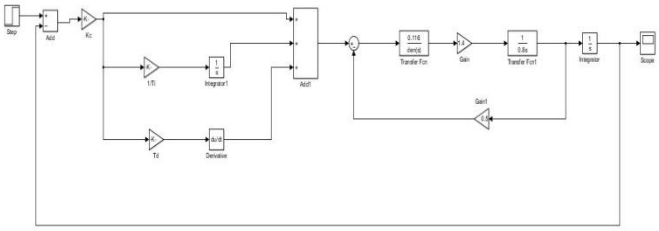

Fig 4.18.Simulation diagram of BLDC motor with PID controller

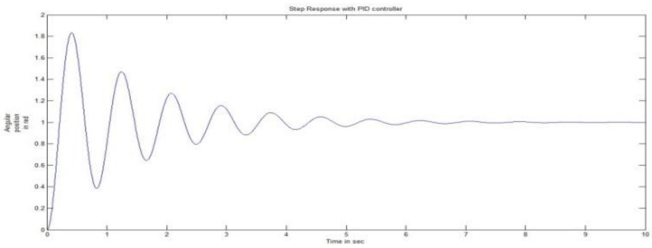

Fig 4.19.Step response of BLDC motor with PID controller

Bode plot for position control of BLDC motor with PID controller are shown Figure 4.20

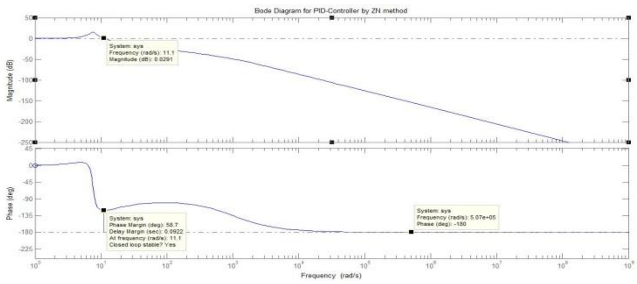

Fig 4.20.Bodeplot for position control of BLDC motor with PID controller

4.2. Tyreus-Luyben method

The Tyreus-Luyben tuning procedure is quite similar to Ziegler Nichols tuning procedure but controller settings are different. The settings that are based on the gain (Ku) and time period (t_u) are shown in the table below.

The gain and time period for the position controlled BLDC motor obtained in the Ziegler Nichols method are, gain Ku=507.32 and time period t_u=0.6169.

4.2.1. Proportional controller (P controller)

By Tyreus-Luyben tuning rules,

$K_p = 0.3125K_u \Rightarrow K_P = 0.3125 * 507.32 \Rightarrow K_p = 158.54$

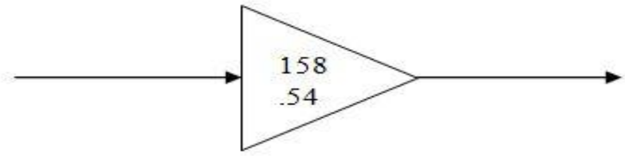

Fig 4.21.Proportional controller

Apply step input to the BLDC motor with proportional controller the response will be as shown in figure 4.23.

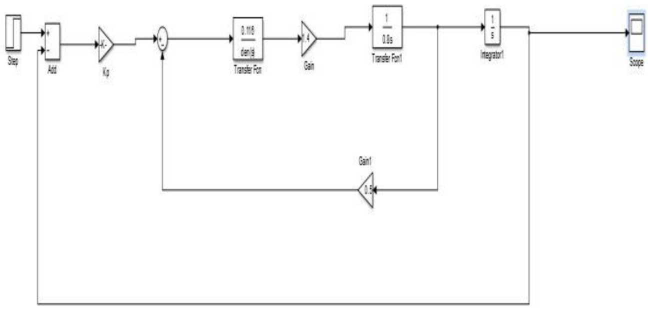

Fig 4.22.Simulation diagram of BLDC motor with Proportional controller

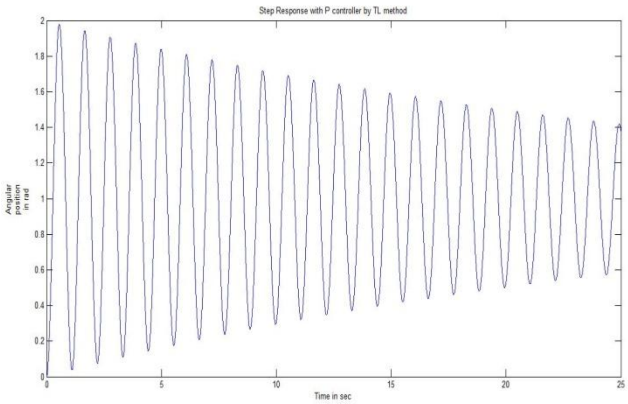

Fig 4.23.Step response of position control of BLDC motor with P-controller

Bode plot for position control of BLDC motor with Proportional controller is shown Figure 4.24

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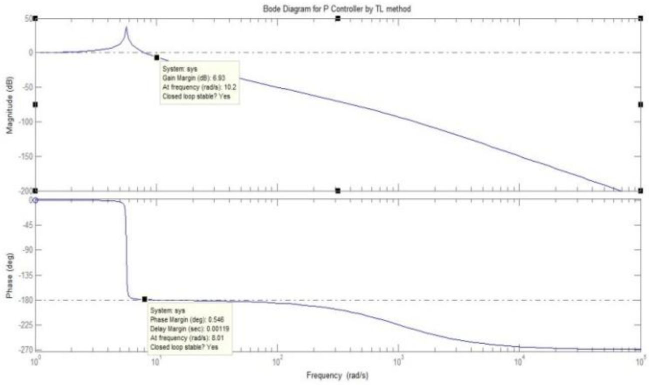

Fig 4.24.Bodeplot for position control of BLDC motor with Proportional controller

4.2.2. PI controller

By Tyreus-Luyben tuning rules,

$K_p = 0.3125 t_u \Rightarrow K_p = 0.3125 * 507.32 \Rightarrow K_p = 158.54$

$T_i = 2.2 t_u \Rightarrow T_i = 2.2 * 0.6169 \Rightarrow T_i = 1.3572$

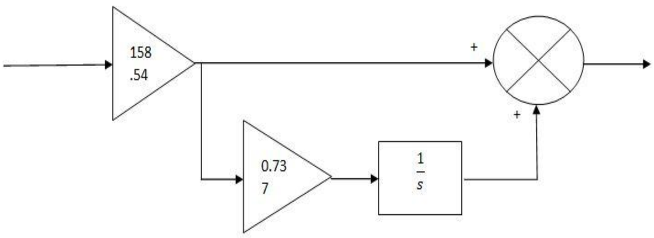

Fig 4.25.PI controller

Apply step input to BLDC motor with PI-Controller, The response is as shown in figure 4.27.

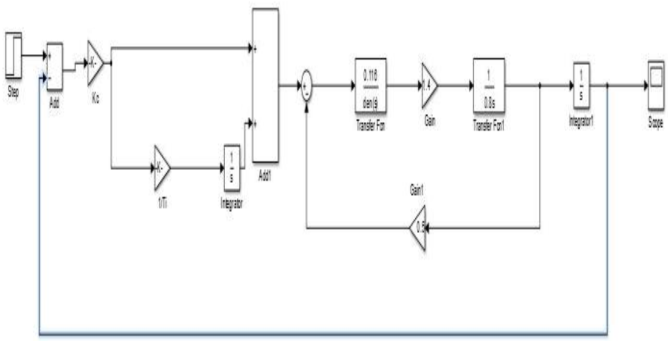

Fig 4.26.Simulation diagram of BLDC motor with PI Controller

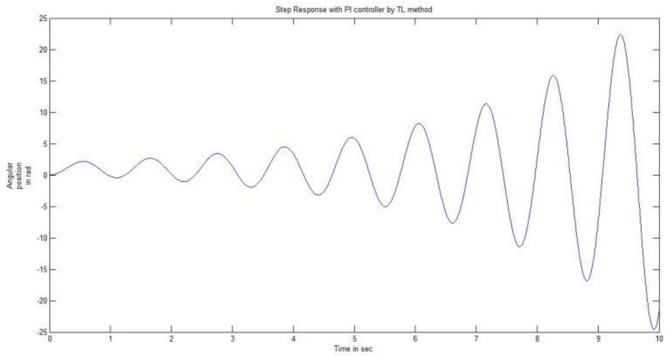

Fig 4.27.Step response of BLDC with PI controller

Bode plot for position control of BLDC motor with PI controller is Figure 4.28.

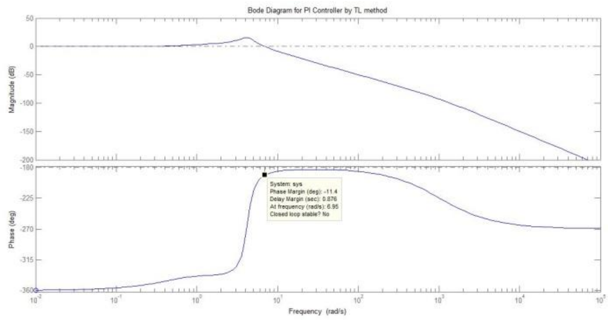

Fig 4.28.Bodeplot for position control of BLDC motor with PI controller

4.2.3. PD controller

By Tyreus-Luyben tuning rules,

$K_p = 0.3125 K_u \Rightarrow K_p = 0.3125 * 507.32 \Rightarrow K_p = 158.54$

$T_d = 0.152 t_u \Rightarrow T_d = 0.152 * 0.6169 \Rightarrow T_d = 0.098$

The transfer function of PD controller is

$G_c(s) = 158.54(1 + 0.0098s)$

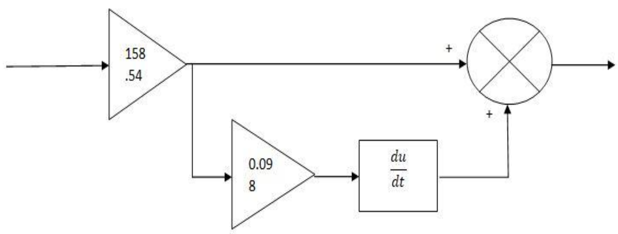

Fig 4.29.PD controller

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Apply step input to the BLDC motor with PD controller, the response is shown in figure 4.31

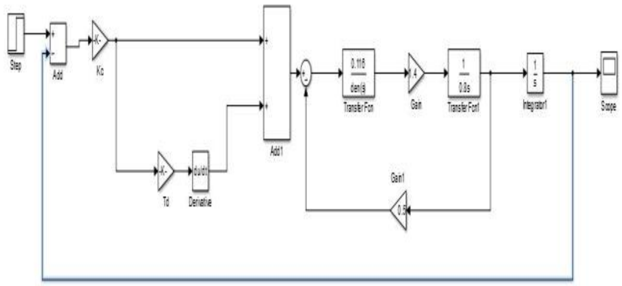

Fig 4.30.Simulation diagram of BLDC with PD controller

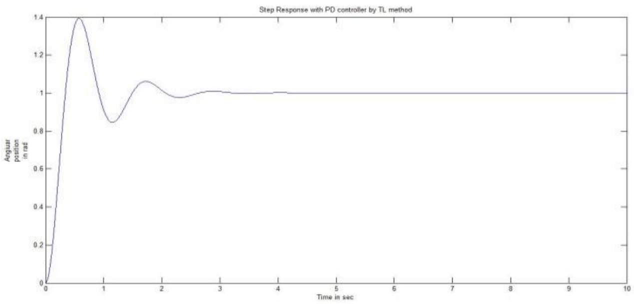

Fig 4.31.Step response of BLDC motor with PD controller

Bode plot for position control of BLDC motor with PD controller is shown in Figure 4.32

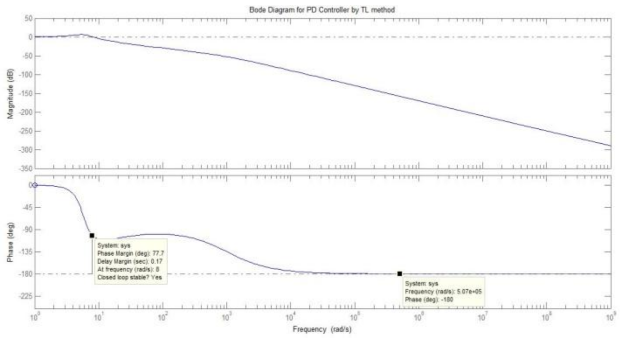

Fig 4.32.Bodeplot for position control of BLDC motor with PD controller

4.2.4. PID controller

By Tyreus-Luyben tuning rules

$K_p =$

$0.3125K_u \Rightarrow K_p = 0.3125 * 507.32 \Rightarrow K_p = 158.54$

$T_i = 2.2t_u \Rightarrow T_i = 2.2 * 0.6169 \Rightarrow T_i = 1.3572$

$T_d = 0.152t_u \Rightarrow T_d = 0.152 * 0.6169 \Rightarrow T_d = 0.098$

The transfer function of controller is

$G_c(s) = 158.54(1 + \frac{1}{1.357s} + 0.0098s)$

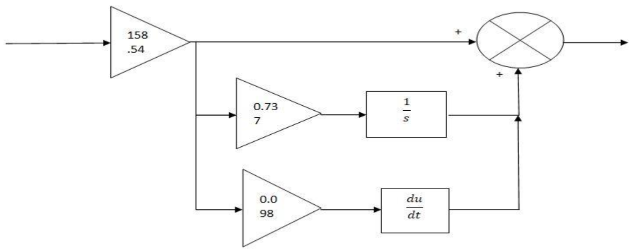

Fig 4.33.PID controller block diagram

Apply step input to to the BLDC motor with PID controller, the response is shown in figure 4.35

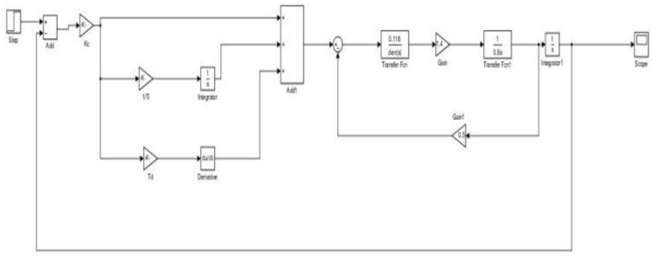

Fig 4.34.Simulation diagram of BLDC motor with PID controller

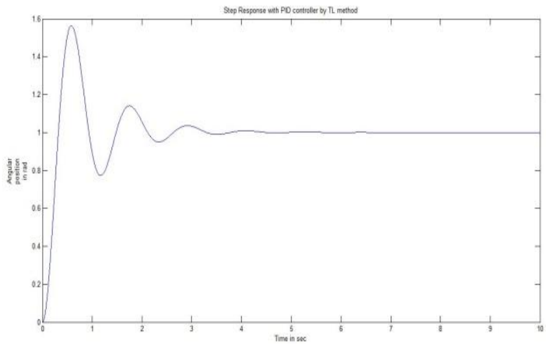

Fig 4.35.Step response of BLDC motor with PID controller

Bode plot for position control of BLDC motor with PID controller are shown Figure Figure 4.36

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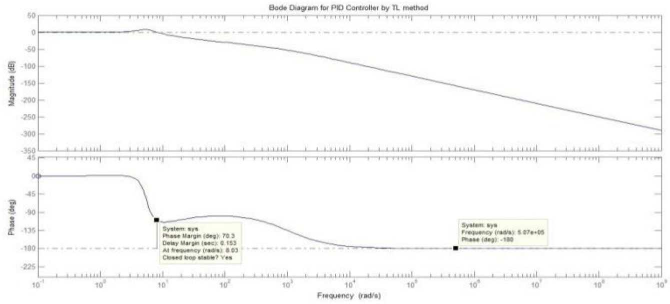

Fig 4.36.Bodeplot for position control of BLDC motor with PID controller

RESULTS DESCUSSION AND CONCLUSIONS

Table 4.1 Comparison of time domain specifications for different controllers for Ziegler-Nichols method

parameter	P-controller	PI-controller	PD-controller	PID-controller
Rise time	0.1331	NaN	0.1311	0.1215
Settling time	192.0553	NaN	1.6446	5.8141
Overshoot	99.1830	NaN	44.2970	69.9750
peak	1.9918	Inf	1.4430	1.6997
Peak time	0.4001	Inf	0.3442	0.3410
zeta	0.0026	-0.1696	0.3060	0.0863
Steady state error	0.02	inf	0.01	0.02

Table 4.2 Stability margins with different controllers by Ziegler-Nichols method

Parameter	P-controller	PI-Controller	PD-controller	PID-controller
Gain margin	-3.34	-	-	-
Phase margin	-0.205	-32.7	81	58.7
Gain crossover frequency	11.1	11.1	11.1	11.1

Phase crossover frequency	10.2	--	5.02e+05	5.07e+05

Table 4.19 comparison of time domain specification for different controller for Tyreus-Luyben method

parameter	P-controller	PI-controller	PD-controller	PID-controller
Rise time	0.1849	-	0.1839	0.1785
Settling time	111.9972	-	2.3449	2.9836
Overshoot	98.0826	*-	45.8948	55.8297
peak	1.9908	Inf	1.4589	1.5583
Peak time	0.5544	Inf	0.4772	0.4903
zeta	0.0062	-0.0778	0.2891	0.2219
Steady state error	0.02	inf	0.01	0.02

Table 4.20 Stability margins with different controllers by Tyreus-Luyben method

Parameter	P-controller	PI-Controller	PD-controller	PID-controller
Gain margin	6.93	-	-	-
Phase margin	0.546	-11.4	77.7	70.3
Gain crossover frequency	8.01	6.95	8	8.03
Phase crossover frequency	10.2	--	5.02e+05	5.07e+05

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Comparison of time domain specification for

From the comparison for Ziegler-Nichols method and Tyrues-Luyben methods the Rise time, Peak time and % overshoot are high in TL method compared to ZN method for all the controllers. The settling time is less in TL method compared to ZN method and the steady state error is same in both methods for the respective controllers.

By comparing different controllers

Rise time is same in P and PD controllers and it is increased in PID controller.

Peak time is more in P controller and less in both PD & PID controllers.

% Overshoot is high in P controller low in PD controller, for PID controller is higher than PD controller and lower than P controller

Settling time is very high in P controller compared to PD and PID controllers, its least for PD controller.

Steady state error is same for P & PID controllers and less in PD controller

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