Modeling and Performance Analysis of PID Controlled BLDC Motor and Different Schemes of PWM Controlled BLDC Motor

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Abstract- Brushless dc (BLDC) motor drives are continually gaining popularity in motion control applications. Therefore, it is necessary to have a low cost, but effective BLDC motor speed/torque regulator. They are used in Residential and commercial appliances such as refrigerators and air conditioning systems with conventional motor drive technology. A Brushless DC (BLDC) drives are known for higher efficiency and lower maintenance. This paper presents a “Modeling and performance analysis of PID controlled BLDC motor and different schemes of PWM controlled BLDC motor”. This paper presents PID model of brushless dc (BLDC) motor with the use of MATLAB/ SIMULINK. The operational parameters of specific BLDC motor were modeled using the tuning methods which are used to develop subsequent simulations.

Index Terms- Brushless DC motor (BLDCM), Digital pulse width modulation (DPWM) PID controllers

I. INTRODUCTION

The use of the general type dc motor has its long history. It has been used in the industries for many years now. They provide simple means and precise way of control [1]. In addition, they have high efficiency and have a high starting torque versus falling speed characteristics which helps high starting torque and helps to prevent sudden load rise [2]. the brushless direct current (BLDC) motor are gaining grounds in the industries ,especially in the areas of appliances production ,aeronautics ,medicine, consumer and industrial automations and so on.

The BLDC are typically permanent synchronous motor, they are well driven by dc voltage. They have a commutation that is done mainly by electronics application.

Some of the man y advantages of a brushless dc motor over the conventional brushed dc motors are highlighted below [3]:

1. Better speed versus torque characteristics
2. High dynamic response
3. High efficiency
4. Long operating life
5. High speed ranges
6. Low maintenance (in terms of brushes cleaning; which is peculiar to the brushed dc motor).

The PID controller is applied in various fields of engineering, and it is also a very important tool in telecommunication system. If there is a system and stability is desired, then PID could be very useful. In practice, the design of the BLDCM drive involves a complex process such as modeling, control scheme selection, simulation and parameters tuning etc. An expert knowledge of the system is required for tuning the controller parameters of servo system to get the optimal performance. Recently, various modern control solutions are proposed for the speed control design of BLDC motor [4]. However, Conventional PID controller algorithm is simple, stable, easy adjustment and high reliability, Conventional speed control system used in conventional PID control [5]. But, in fact, most industrial processes with different degrees of nonlinear, parameter variability and uncertainty of mathematical model of the system. Tuning PID control parameters is very difficult, poor robustness, therefore, it's difficult to achieve the optimal state under field conditions in the actual production.. pwm control method is a better method of controlling, to the complex and unclear model systems, it can give simple and effective control.
Proportional-integral (PI) control with hysteresis or pulse width modulation (PWM) switching is the most widely used speed control technique for BLDC motors with trapezoidal back EMF. It can be easily implemented on analog or digital components because it is well understood, simple, and in practice for a fairly long period of time. To enhance the performance or to reduce the cost has been focus of development work for a long time. Cost and implementation complexity are often the most important factors for design trade-offs between techniques, implementation, and strategy of motor control hardware. The aim of this paper is that it shows the dynamics response of speed with design the PID controller to control a speed of motor for keeping the motor speed to be constant when the load varies.

II. BRUSHLESS DC MOTOR AND MODEL CONCEPT

One of the major differences between the DC motor and the BLDC is implied from the name. the conventional dc motor has brushes that are attached to its stator while the “brushes” DC motor does not. Also, unlike the normal DC motor, the commutation of the BLDC could be done by electronic control [3]. Under the BLDC motor, the stator windings are energized in sequence for the motor to rotate. More also, there is no physical contact whatsoever between the stator and the rotor. Another vital part of the BLDC is the hall sensor(s); these hall sensors are systematically attached to the rotor and they are used as major

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sensing device by the Hall Effect sensor embedded into the stator [3]. This works based on the principal of Hall Effect.

The BLDC motor operates in many modes (phases), but the most common is the 3-phase. The 3- phase has better efficiency and gives quite low torque. Though, it has some cost implications, the 3-phase has a very good precision in control [6]. And this is needful in terms of the stator current.

2.1 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 the phase involved which affects the overall result of the BLDC model. The phase peculiarly affects the resistive and the inductive of the BLDC arrangement.

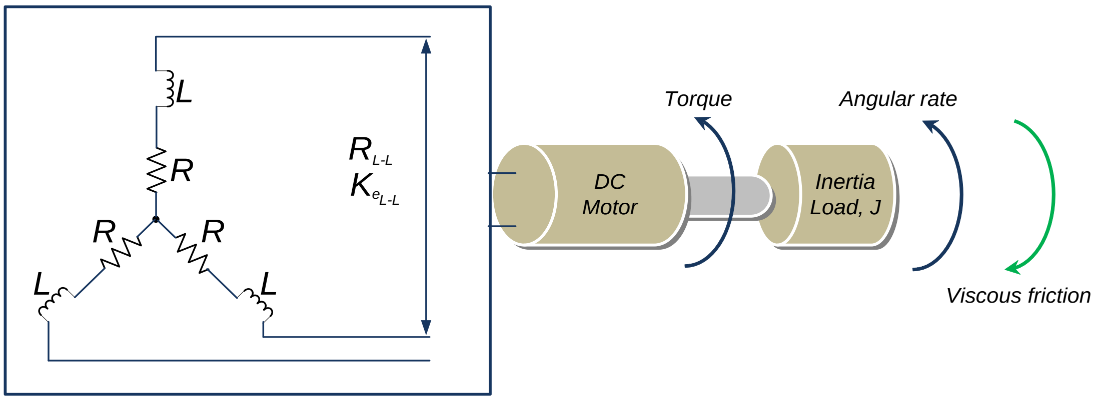

Fig.1. Brushless DC motor schematic diagram

For the mechanical time constant (with symmetrical arrangement), equation becomes:

$$\tau_m = \sum \frac{RJ}{K_e K_t} = \frac{J \sum R}{K_e K_t} \qquad (2.1)$$

the electrical (time constant),

$$\tau_e = \sum \frac{L}{R} = \frac{L}{\sum R} \qquad (2.2)$$

Therefore, since there is a symmetrical arrangement and a there phase, the mechanical (known) and electrical become:

Mechanical constant,

$$\tau_m = \frac{J.3R}{K_e K_t} \qquad (2.3)$$

Electrical constant,

$$\tau_e = \frac{L}{3.R} \qquad (2.4)$$

Where,

$K_e = \left[\frac{\mathrm{V-secs}}{\mathrm{rad}}\right]$: the electrical torque

$K_t = \left[\frac{\mathrm{N-m}}{\mathrm{A}}\right]$: the torque constant

Therefore, the equation for the BLDC is

$$G(s) = \frac{\frac{1}{K_e}}{\tau_m \cdot \tau_e \cdot s^2 + \tau_m \cdot s + 1} \qquad (2.5)$$

III. MAXON BLDC MOTOR

3.1 Maxon EC 45 flat Ø 45 mm, brushless DC motor

The BLDC motor provided for this paper is the EC 45 flat Ø45 mm, brushless, 30 Watt from Maxon motors [7]. The order number of the motor is 200142. The parameters used in the modeling are extracted from the datasheet of this motor with corresponding relevant parameters used. Find below in Table 5.1 the major extracted parameters used for the modeling task.

	Maxon Motor Data	**Unit**	**Value**
	<u>Values at nominal voltage</u>		
1	Nominal Voltage	V	12.0
2	No load Speed	rpm	4370
3	No load Current	mA	151
4	Nominal Speed	rpm	2860
5	Nominal Torque (max. continuous torque)	mNm	59.0
6	Nominal Current (max. continuous current)	A	2.14
7	Stall Torque	mNm	255
8	Starting Current	A	10.0
9	Maximum Efficiency	%	77
	<u>Characteristics</u>		
10	***Terminal Resistance phase to phase***	Ω	1.1

11	***Terminal Inductance phase to phase***	mH	0.50
12	***Torque Constant***	mNm/A	24.5
13	***Speed Constant***	rpm/V	35.4
14	Speed/Torque Gradient	rpm/mNm	17.6
15	***Mechanical time constant***	ms	16.1
16	***Rotor Inertia***	gcm^2	82.5
17	*Number of phase*		3

Table.1. BLDC MOTOR PARAMETERS USED [7]

IV. BLDC Maxon Motor Mathematical Model

The mathematical model of the BLDC motor is modelled on the parameters from table given above.

$$G(s) = \frac{\frac{1}{K_e}}{\tau_m \cdot \tau_e \cdot s^2 + \tau_m \cdot s + 1} \quad \ldots\ldots\ldots\ldots \quad (4.1)$$

So the values for K_e, τ_m and τ_e need to calculated to obtain the motor model

$$\tau_e = \frac{L}{3.R}$$

$$\tau_e = \frac{0.50 \times 10^{-3}}{3 \times 1.10}$$

$$\tau_e = 151.51 \times 10^{-6} \quad \ldots\ldots\ldots\ldots\ldots.. \quad (4.2)$$

But τ_m is a function of R, J, K_e and
Then

$$\tau_m = \frac{3.R_\phi.J}{K_e.K_t} = 0.0161$$

$$K_e = \frac{3.R_\phi.J}{\tau_m.K_t} = \frac{3 \times 1.1 \times 8.25 \times 10^{-6}}{0.0161 \times 24.5 \times 10^{-3}} = 0.06902\,\frac{\text{v} - \text{secs}}{\text{rad}}$$

Therefore, the G(s) becomes:

$$G(s) = \frac{14.48}{151.51 \times 10^{-6} \times 0.0161 \cdot s^2 + 0.0171 \cdot s + 1}$$

$$G(s) = \frac{14.48}{2.44 \times 10^{-6} \cdot s^2 + 0.0161 \cdot s + 1} \quad \ldots\ldots\ldots\ldots\ldots.. \quad (4.3)$$

The G(s) derived above in the equation 4.3 is the open loop transfer function of the Brushless DC maxon motor using all necessarily sufficient parameters available.

4.1 Open Loop Analysis using MATLAB m- file

With the aid of the BLDC motor parameters provided, the open loop analysis is done by considering the stability factors and making the necessary plots for this analysis. Some of the plots include the step response, root locus, nyquist diagram, and bode plot diagram.

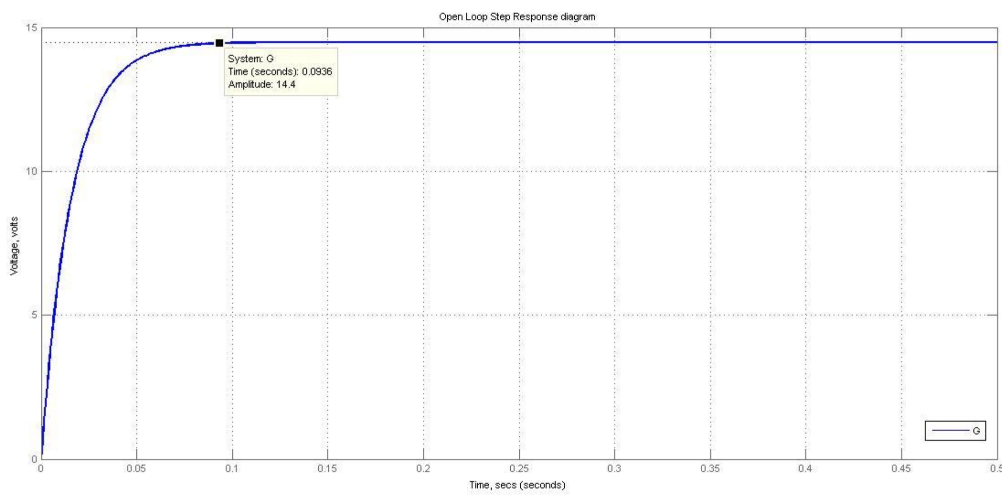

Figure.2. Open loop step response diagram

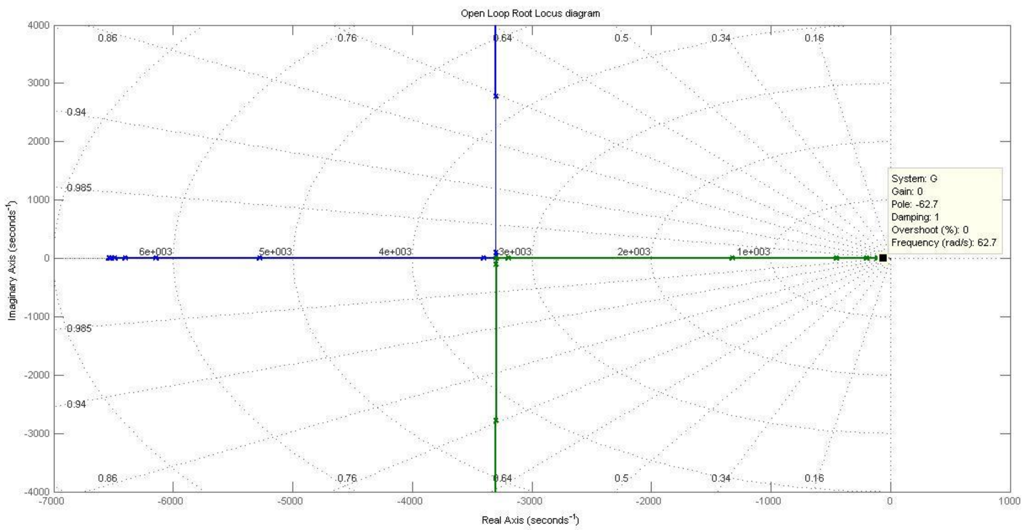

Figure.3. Open loop step root locus diagram

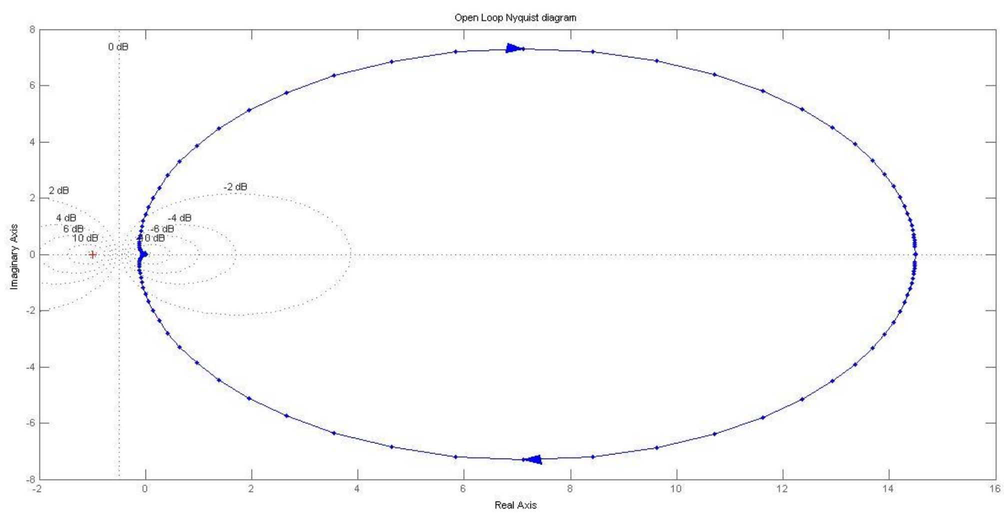

Figure. 4. Open Loop step Nyquist diagram

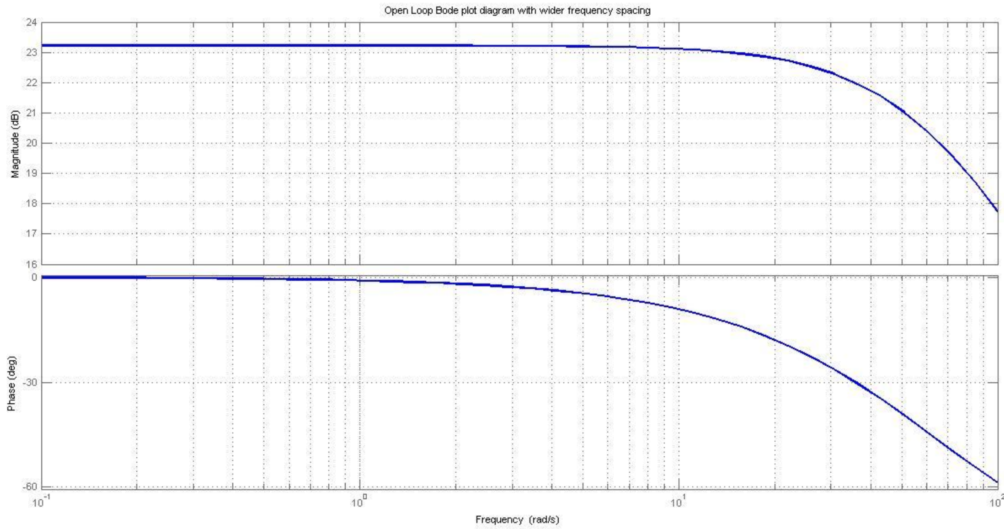

Figure. 5. Open Loop Step Bode Plot diagram

V. PID DESIGN CONCEPT

The Proportional-Integral-Derivative (PID) controller is about the most common and useful algorithm in control systems engineering [8]. In most cases, feedback loops are controlled using the PID algorithm. The main reason why feedback is very important in systems is to be able to attain a set-point irrespective of disturbances or any variation in characteristics of any form. Consider the characteristics parameters – proportional (P), integral (I), and derivative (D) controls, as applied to the diagram below in figure 2, the system, S is to be controlled using the controller, C; where controller, C efficiency depends on the P, I and D parameters [7].

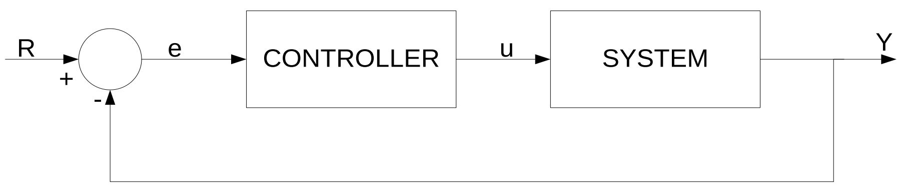

Figure. 6. A typical system with a controller

Typically, the function of the form shown in equation 5.1 is applicable in this kind of PID controller design.

$$K_p + \frac{K_I}{s} + K_D \cdot s = \frac{K_D s^2 + K_P s + K_I}{s} \qquad (5.1)$$

Where,

K_p = Proportional gain
K_I = Integral gain
K_D = Derivative gain

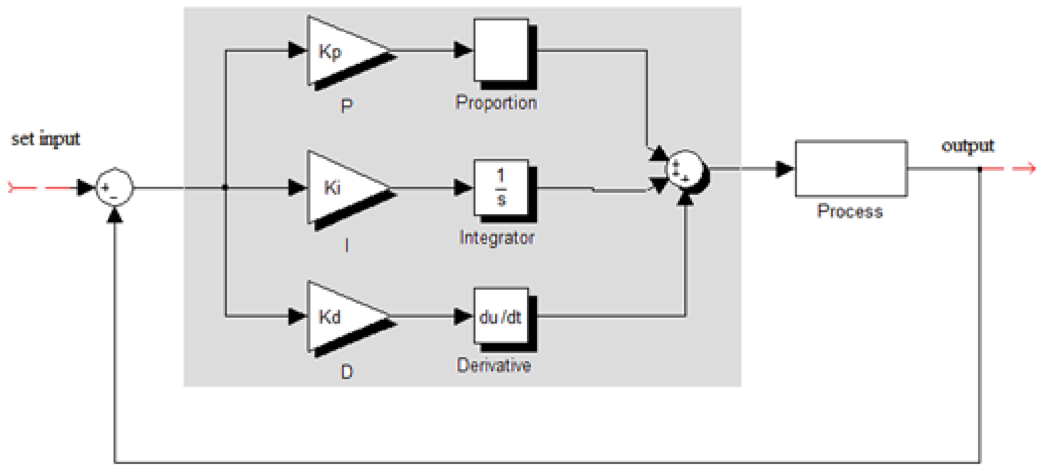

Figure. 7. PID parameters schematics

VI. PID CONTROLLER TUNING PARAMETERS

Under this section a critical analysis would be done on the PID tuning criteria and the parameters involved. Before a detail analysis is done, a quick look at the tuning methods is considered first and thereafter, specific tuning parameters are computed for the BLDC maxon motor. Some of the generally used tuning methods are the Trial and Error method, the Ziegler-Nichols method (1st), *Improved* Ziegler-Nichols method (2nd), Cohen-Coon method, Genetic Algorithms and so on. For this work, the Ziegler-Nichols tuning method would be given a priority.

6.1 Ziegler-Nichols tuning methods

The Ziegler-Nichols method used was done based on obtaining the open loop transfer function and thereafter obtaining the necessary parameter values needed for the various evaluation of the P, PI and PID parameters.

The open loop step response is characterized by two main parameters, the L (delay time parameter) and T (time constant). These two parameters are computed by drawing tangents to the open loop step response at its point of inflections (basically two points. The inflection points are particularly done so that there would be an intersection with the vertical (voltage axis, which correlates with the steady-state value) and horizontal (time axis) axes.

Based on the Ziegler-Nichols, the following were derived to obtain the control parameters based on the required model

	PID Type	K_P	$T_I = \frac{K_P}{K_I}$	$T_D = \frac{K_D}{K_P}$
1.	P	$\frac{T}{L}$	∞	0
2.	PI	$0.9 \times \frac{T}{L}$	$\frac{L}{0.3}$	0
3.	PID	$1.2 \times \frac{T}{L}$	$2 \times L$	$0.5 \times L$

Table.2. Ziegler-Nichols PID controller parameters model [9]

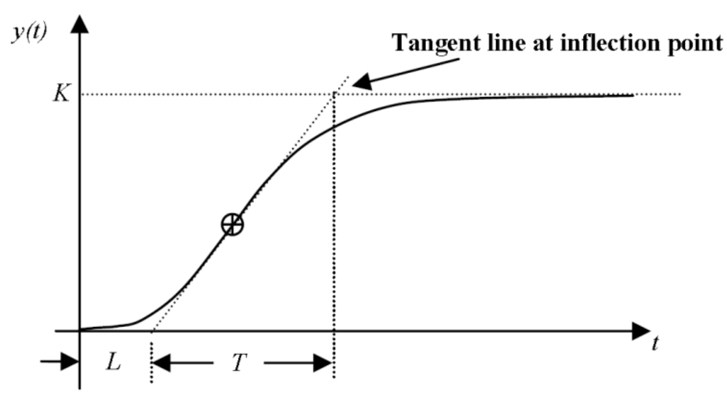

Figure. 8. Ziegler-Nichols step response tuning method [9]

From the Figur, the target is on how to evaluate the two parameters (L and T) needed. This is done as follows with the illustration.

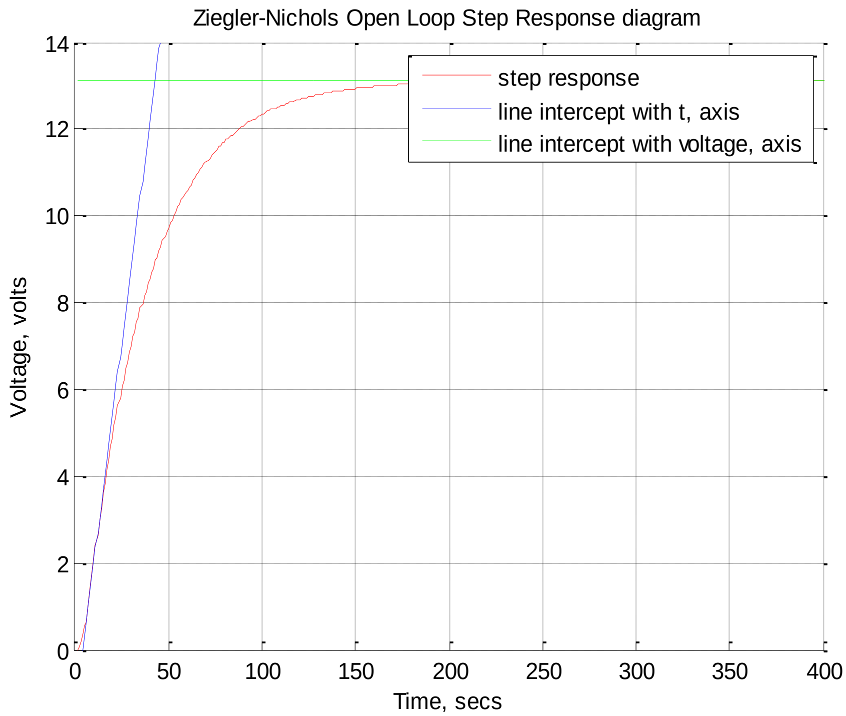

Figure .9 .Ziegler-Nichols open step response plot computation

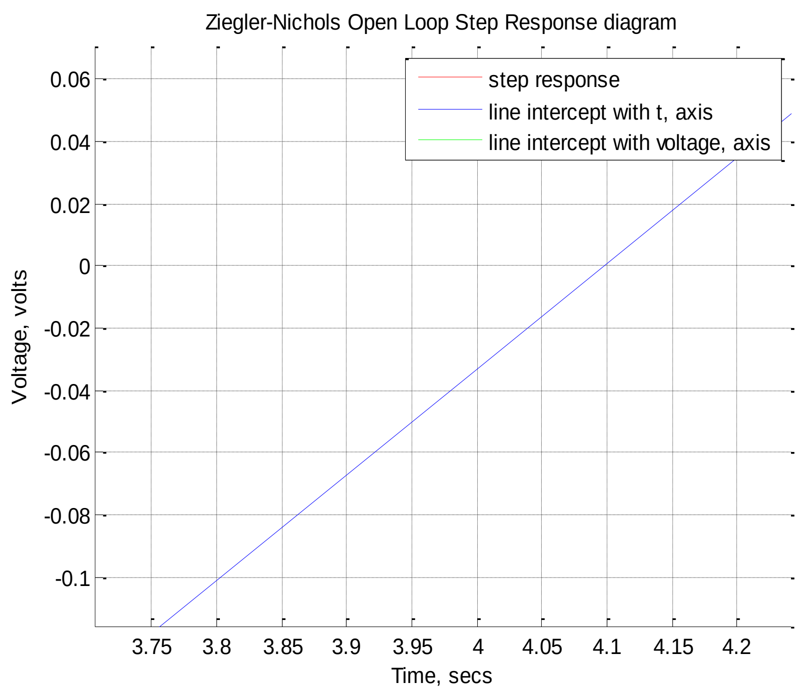

Figure.10. Ziegler-Nichols open step response horizontally zoomed

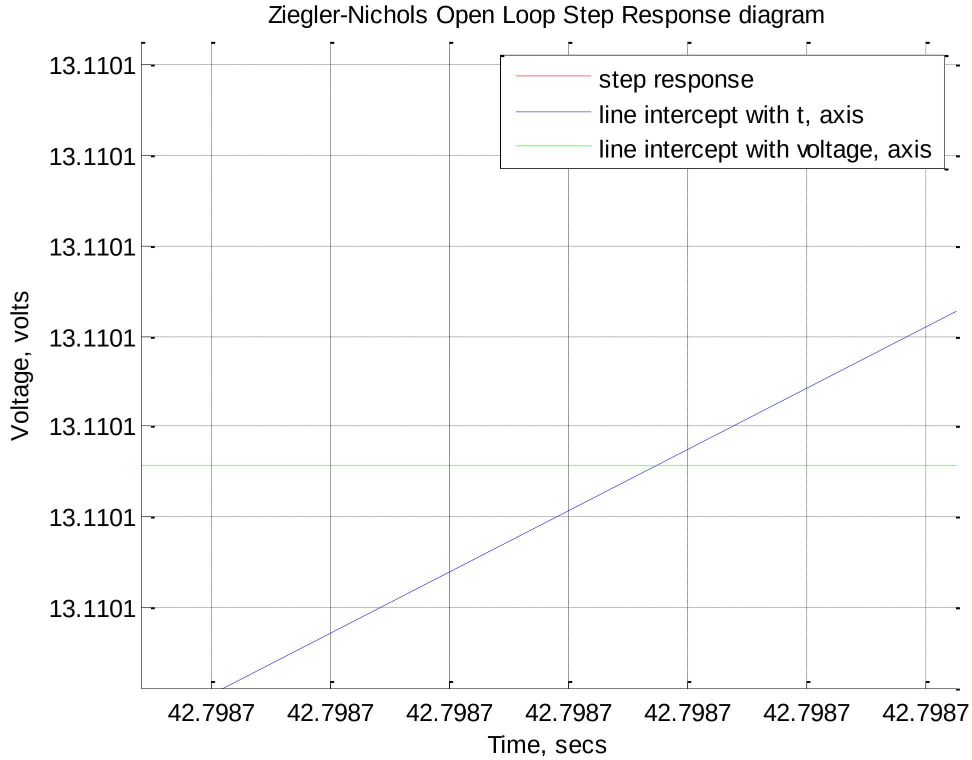

Figure.11. Ziegler-Nichols open step response vertically zoomed

Therefore, from the Figure , Figure and Figure6, the values of the L and T could be computed as follows:

Coordinate of the point of interception of the two lines ≈ (T^*, K) = (42.7987, 13.1101);

Where,

T^* is horizontal trace of the interception on the tangent lines drawn

L = 4.1;

K = 13.1101;

$T = T^* – L = 4.1 = 42.7987 - 38.6987 \approx 38.70$

This implies that we have:

L = 0.0041;

K = 13.1101;

T = 0.0387

With the above computation, the P, PI and PID computation was done to get the best suited parameters combination desired.

So the updated table 9.1 would be table 9.2 shown below:

1.	P	9.439	∞	0
	PID Type	K_p	$T_I = \frac{K_p}{K_I}$	$T_D = \frac{K_D}{K_p}$
2.	PI	8.495	0.0137	0
3.	PID	11.327	0.0082	0.00205

Table.3. Results of the Ziegler-Nichols method for PID controller parameters

From table 9.2, the following parameters are obtained based on the equation format which is given below:

For PID only,

$$K_p + \frac{K_I}{s} + K_D \cdot s = 11.327 + \frac{1381.34}{s} + 0.0232 \cdot s \qquad ($$

The outputs of the various PID combinations could be obtained as given below: using MATLAB Programming.

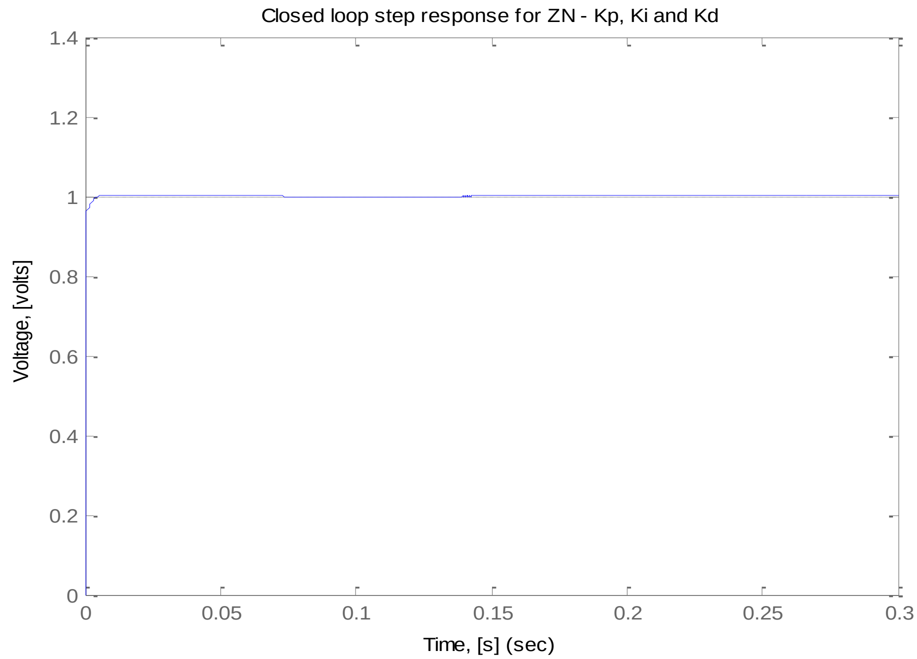

Figure.12. auto- scaled PID output for the Ziegler-Nichols tuning method

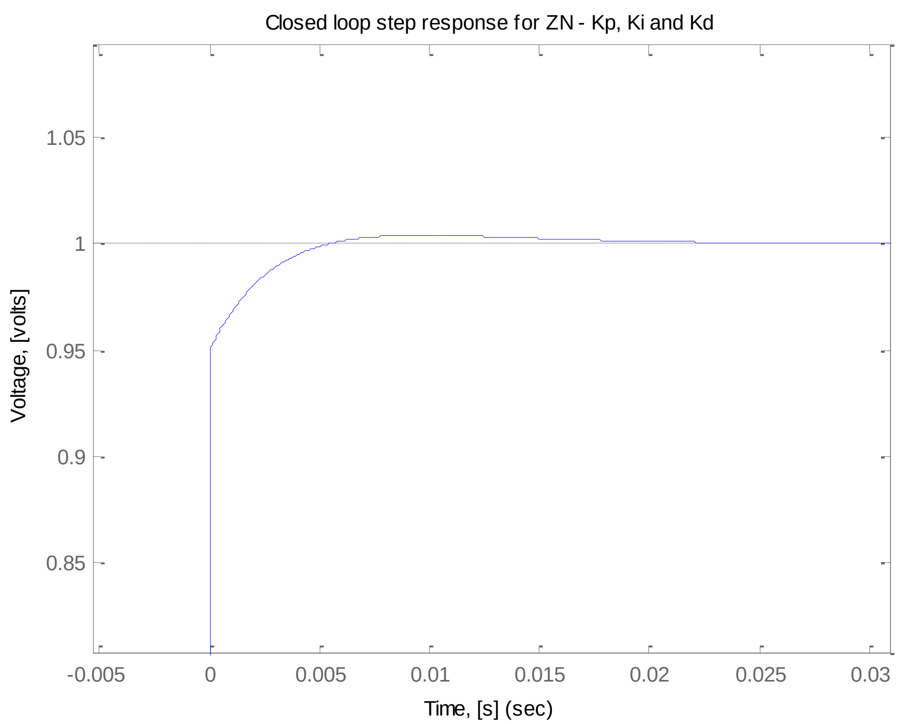

Figure.13. Auto-scaled PID output for the Ziegler-Nichols tuning method (zoomed overshoot point

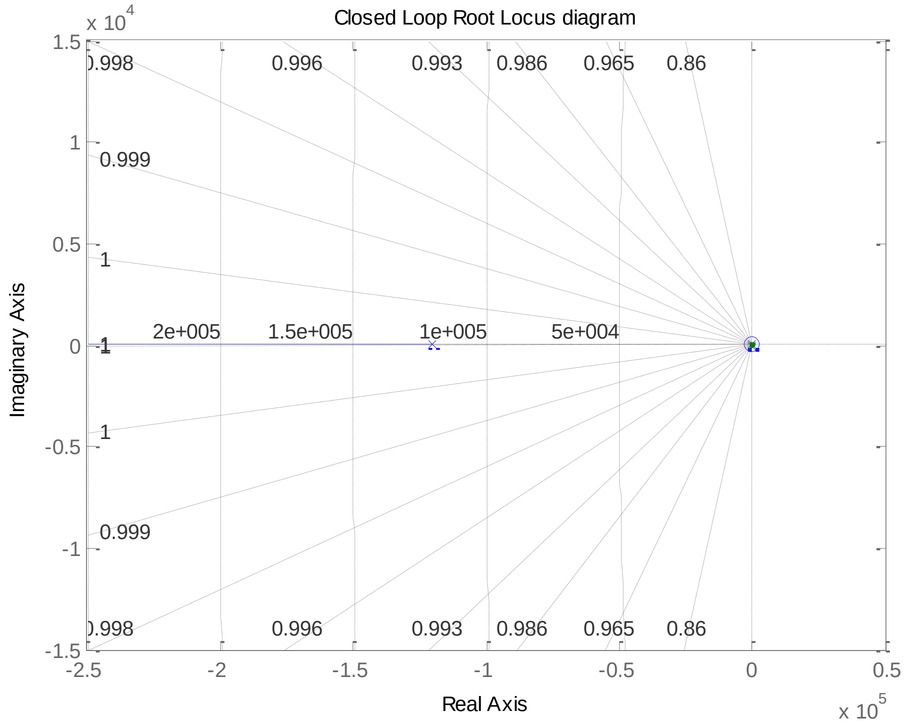

Figure.14. PID Ziegler-Nichols tuning method Root locus diagram

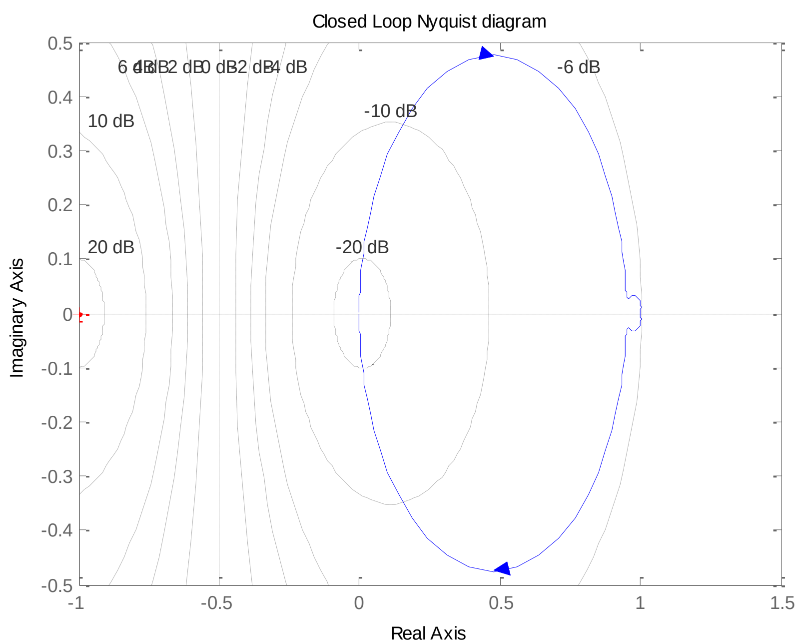

Figure.15. PID Ziegler-Nichols tuning method Nyquist diagram

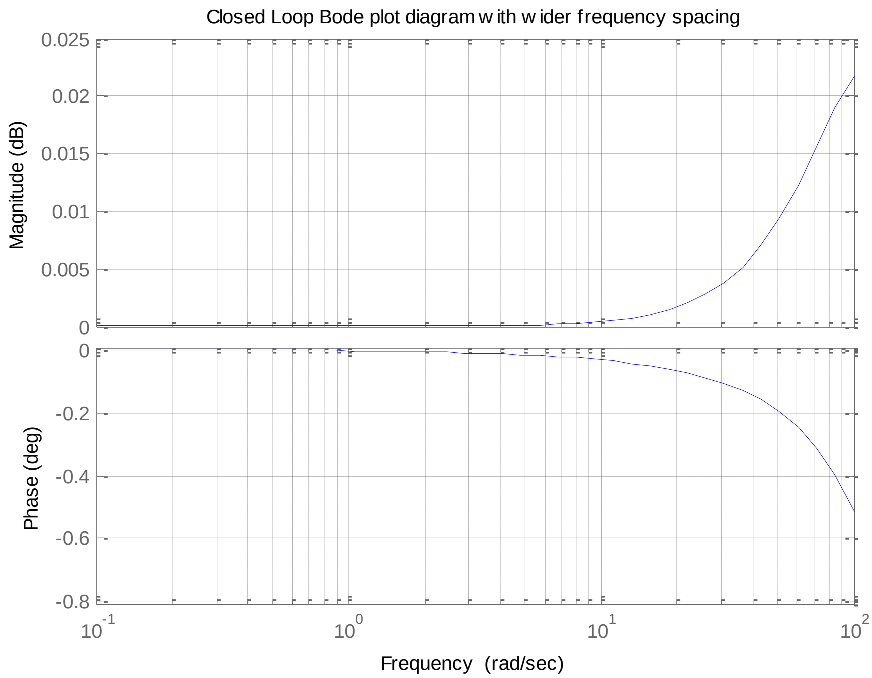

Figure.16. PID Ziegler-Nichols tuning Bode plot diagram

VII. CONVENTIONAL BLDC MOTOR DRIVE SYSTEM

For a three-phase BLDC application, a three-phase inverter bridge [10] is used. The typical inverter drive system for a BLDC motor is shown in Fig. 1. The three phase inverter operation can be divided into six modes (1-6) according to the current conduction states and conduction sequence. The switches in are operated such that each phase carries current only during the 120◦ period when the back EMF is constant.

Thus, there is a commutation event between phases for every 60◦ electrical, as shown in Fig. 2.Appropriate commutation therefore requires knowledge of rotor position, which can be directly detected using position sensors or estimated in sensorless manner by monitoring back EMF in the open phase . The three phase currents are controlled to take a form of quasi square waveform in order to synchronize with the trapezoidal back EMF to produce constant torque. This task is performed by speed/torque control loop in cooperation with rotor position sensor and hysteresis current controller.

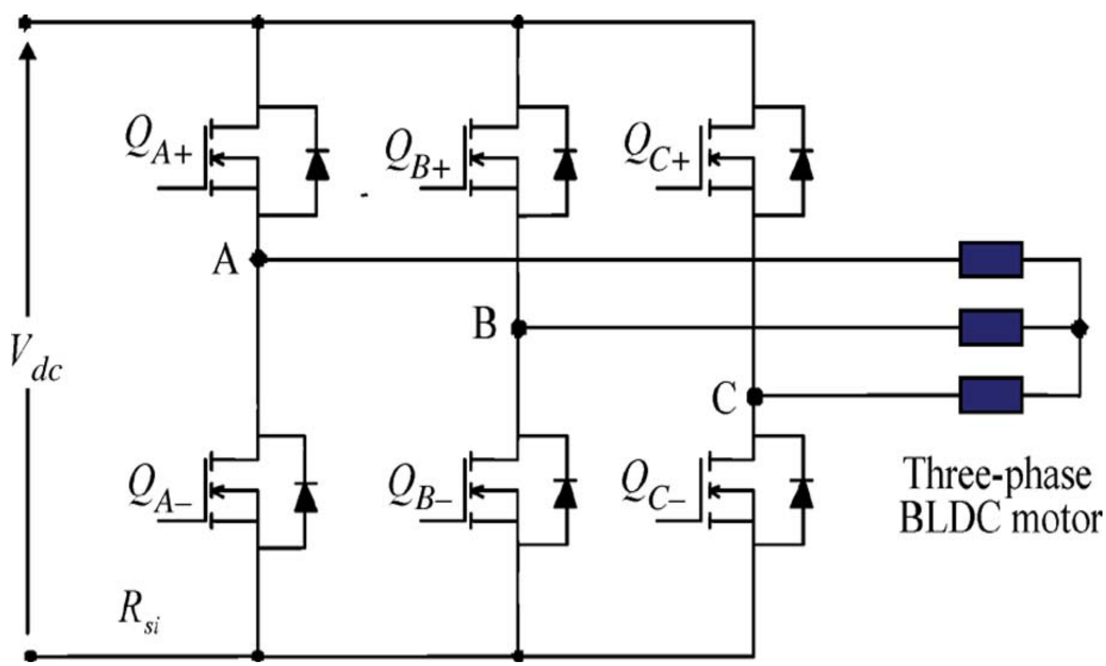

Fig.17. Typical inverter-fed BLDC motor drive system

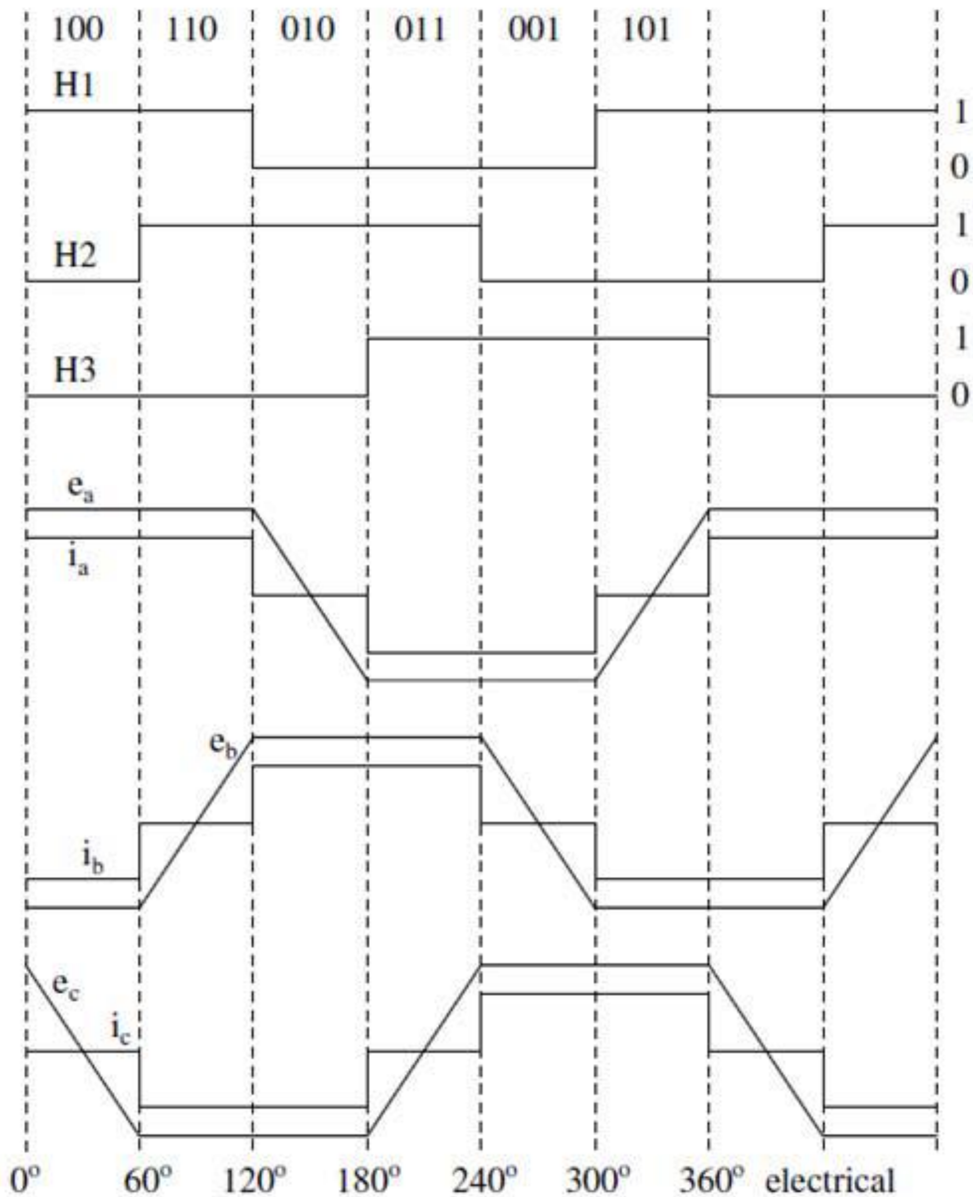

Fig.18. Hall sensor signal and Trapezoidal back EMF

Speed control in a BLDC involves changing the applied voltage across the motor phases [10]. This can be done using a sensored method based on the concept of pulse amplitude modulation, PWM, or hysteresis control. A common control algorithm for a permanent-magnet BLDC motor is PWM current control. It is based on the assumption of linear relationship between the phase current and the torque, similar to that in a brushed dc motor. Therefore, by adjusting phase current, the electromagnetic torque can be controlled to meet the requirement. Instantaneous current in the motor is regulated in each phase by a hysteresis regulator, which maintains the current within adjustable limits. The rotor position information is sensed to enable commutation logic, which has six outputs to control the upper and lower phase leg power switches. The current reference is determined by a PI regulator, which maintains the rotor average speed constant

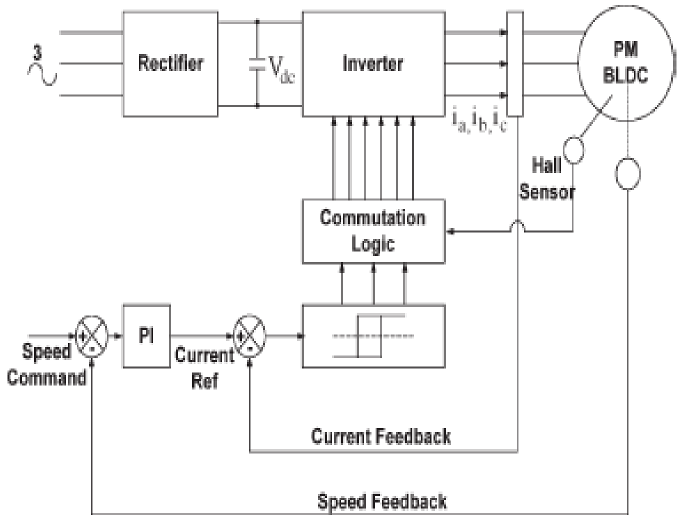

Fig.19. conventional PWM control scheme

VIII. DIGITAL PWM CONTROL SCHEME

The concept of this digital controller is very simple. Speed regulation is achieved by using two levels of duty cycles-a high duty (*DH*) and a low duty (*DL*)[11]. In essence, the controller treats the BLDC motor as a digital system, which may operate in two predefined states, namely state-1 and state-2[12]. These states are corresponding to two speeds *WL* (< than reference speed) and *WH* (> reference speed) and the speed regulation by appropriately altering the states.

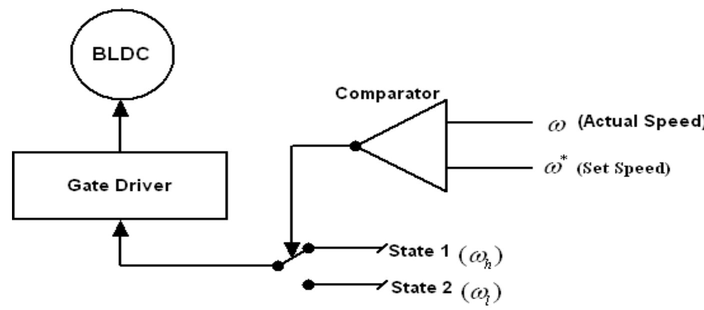

Fig.20. principal of operation of Digital controller

a) If the motor speed is less than commanded speed, then switch or stay at state-2 (*WH*)

b) If the motor speed is greater than commanded speed, then switch or stay at state-1 (*WL*)

Unlike a hysteresis current controller, a PWM control does not have an inherent current control capability. Hence, a current limiter has to be introduced [11]. A proportional controller provides the reference for the current limit. The current is always made to stay within a maximum and minimum limit. The maximum value of *I limit* is 1.5 times the rated motor current. This is because motors can handle 1.5 times the rated current for a short duration of time. The minimum value of *Ilimit* is defined as the ratio of a percentage (1%) of the rated torque to the torque constant.Fig.5. shows the block schematic of the digital PWM control of BLDC motor drives.

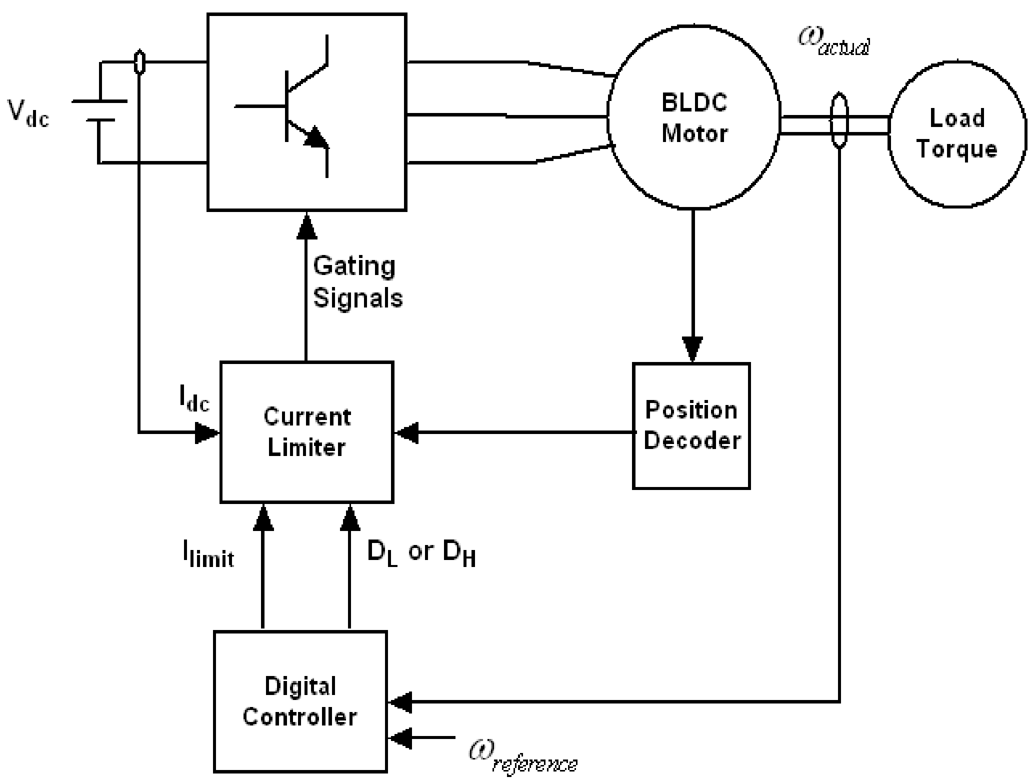

Fig.21. proposed Digital Control

IX. CONTROLLER DESIGN

The value of the duty ratio *D* can be obtained from the electrical and mechanical equations[11]. The value of *D* can be expressed as a function of the motor parameters. From the torque equation, we have

Tem= Jdw÷dt + Bw + Tl ……………. (9.1)
Tem = Ktl ………….. (9.2)

Where *Te*, w(t), *B* , *J* and *TL* denote developed electromagnetic torque, rotor angular velocity, viscous friction rotor moment of inertia and load torque respectively.

Equate (9.1) and (9.2), we get
Ktl = Jdw÷dt + Bw + Tl ………………. (9.3)

where *Kt* = torque constant and *I* = average current. At steady state, (3) can be written in terms of steady-state angular velocity Wss as

I(wss) =(BWss+ Tl)÷Kt …………….. (9.4)

At steady state angular velocity *Wss* , phase voltage *Van* can be expressed in terms of phase current I, winding resistance and velocity constant *ke*, ie given by

Van = IRa + KeWss ………… (9.5)

The phase voltage in terms of dc-link voltage *V*dc and duty ratio *D* is
Van = DVdc …………… (9.6)

Substituting the value of the steady-state current from (9.4) and phase voltage from (9.6) in (9.5),we get the value of duty ratio
D = [(Tl+BWss)÷Kt + KeWss]÷Vdc ……. (9.7)

By considering *WL* and *WH* we can get the *DL* and *DH* respectively.

The maximum deviation from the reference speed (*W**) due to the application of high duty *DH* is denoted by *ΔωH*, and the maximum deviation from the reference speed due to the application of a low duty *DL* is denoted by *ΔωL*. The speed response can be expressed as

W(t) = (Tem- Tl)÷B + [W-(Tem- Tl)÷B]e-(J\B)t …… (9.8)

X. CONCLUSION

The modeling and the simulation of PID control of BLDC motor speed and its torque results are tested.it started with the analysis and reasons why an absolute précised control is important in drives particularly the BLDC motor and then the mathematical modelling.in this paper the open loop analysis is done by considering the stability factor and making the necessary plot for this analysis. some of the plots include the step response, root locus, nyquist diagram, and bode plot diagram. Also study the different schemes of pwm controlled BLDC motor.

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