MS. JULI SINGH / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 3, May-Jun 2012, pp.2868-2884

ANALYSIS THE SPEED CONTROL OF BLDC MOTOR DRIVE USING SENSORS

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ABSTRACT

Brushless DC Motor (BLDC) is one of the best electrical drives that have increasing popularity, due to their high efficiency, reliability, good dynamic response and very low maintenance.Due to the increasing demand for compact & reliable motors and the evolution of low cost power semiconductor switches and permanent magnet (PM) materials, brushless DC motors become popular in every application from home appliances to aerospace industry. The conventional techniques for controlling the stator phase current in a brushless DC drive are practically effective in low speed and cannot reduce the commutation torque ripple in high speed range.

This paper presents the PI controller for speed control of BLDC motor. The output of the PI controllers is summed and is given as the input to the current controller. The mathematical modeling of BLDC motor is also presented. The BLDC motor is fed from the inverter where the rotor position and current controller is the input.

The complete mathematical model of the proposed drive system is developed and simulated using MATLAB/Simulink software. The operation principle of using component is analysed and the simulation results are presented in this to verify the theoretical analysis.

Keywords:BLDCM- BRUSHLESS DIRECT CURRENT MOTOR, PM- PERMANENT MAGNET, PI-Proportional Integrated controller, VR- Variable Reluctance.

1. INTRODUCTION OF BLDCM

The increase in energy prices spurs higher demands of variable speed PM motor drives. Also, recent rapid proliferation of motor drives into the automobile industry, based on hybrid drives, generates a serious demand for high efficient PM motor drives, and this was the beginning of interest in BLDC motors.

BLDC motors, also called Permanent Magnet DC Synchronous motors, are one of the motor type that have more rapidly gained popularity, mainly because of their better characteristics an performance [2]. These motors are used in a great amount of industrial sectors because their architecture is suitable for any safety critical applications.

In general, the overall system consists of three parts: (1) power conversion three phase inverters, (2) BLDC motor and load, (3) speed, torque, and current controllers and (4) Position Control by using sensors. Therefore, exact understanding of each part is a prerequisite for analysis and prediction of the overall system operation.

Several simulation models have been proposed for the analysis of BLDC motor drives. These models are based on state-space equations, Fourier series, and the d-q axis model [9–12].The brushless DC motor is a synchronous electric motor that, from a modeling perspective, looks exactly like a DC motor, having a linear relationship between current and torque, voltage and speed (rad/sec). It is an electronically controlled commutation system, instead of having a mechanical commutation, which is typical of brushed motors. Additionally, the electromagnets do not move, the permanent magnets rotate and the armature remains static. This gets around the problem of how to transfer current to a moving armature. In order to do this, the brush-system/commutator assembly is replaced by an intelligent electronic controller, which performs the same power distribution as a brushed DC motor [3]. BLDC motors have many advantages over brushed DC motors and induction motors, such as a better speed versus torque characteristics, high dynamic response, high efficiency and reliability, long operating life (no brush erosion), noiseless operation, higher speed ranges, and reduction of electromagnetic interference (EMI).

The control of BLDC motors can be done in sensor or sensorless mode, but to reduce overall cost of actuating devices, sensorless control techniques are normally used. The advantage of sensorless BLDC motor control is that the sensing part can be omitted, and thus overall costs can be considerably reduced.

The disadvantages of sensorless control are higher requirements for control algorithms and more complicated electronics [3]. All of the electrical motors that do not require an electrical connection (made with brushes) between stationary and rotating parts can be considered as brushless permanent magnet (PM) machines [4], which can be categorized based on the PMs mounting and the back-EMF shape. The PMs can be surface mounted on the rotor (SMPM) or installed inside of the rotor (IPM) [5], and the back-EMF shape can either be sinusoidal or trapezoidal.

A PMAC motor is typically excited by a three-phase sinusoidal current, and a BLDC motor is usually powered by a set of currents having a quasi-square waveform [6,7].

Brushless DC motors were developed from conventional brushed DC motors with the availability of solid state power semiconductors. Brushless DC motors are similar to AC synchronous motors. The major difference is that synchronous motors develop a sinusoidal back EMF, as compared to a rectangular, or trapezoidal, back EMF for brushless DC motors. Both have stator created rotating magnetic fields producing torque in a magnetic rotor.

The remainder of the paper is arranged as follows. Section -2 discussAnalysis of BLDC motor drive system. Next, section -3 explains the problem identification in bldc motor drive, in this section we discuss problem related to position and speed control of BLDC motors drive using sensors and also describeproblems occur in selecting the value of PI controller gain Section -4 , discuss methodology of BLDC motor drive. Finally in section -5 shows the results analysis of BLDC motor drive and conclusion.

2. Analysis of BLDC Motor Drive System

Figure 1 shows the overall system configuration of the three-phase BLDC motor drive. The three phase inverter topology is a six-switch voltage-source configuration with constant dc-link voltage (Vdc), which is identical with the induction motor drives and the permanent magnet ac motor drives. The analysis is based on the following assumption for simplification [12]:

1. The motor is not saturated.
2. Stator resistances of all the windings are equal, and self- and mutual inductances are constant.
3. Power semiconductor devices in the inverter are ideal.
4. Iron losses are negligible.

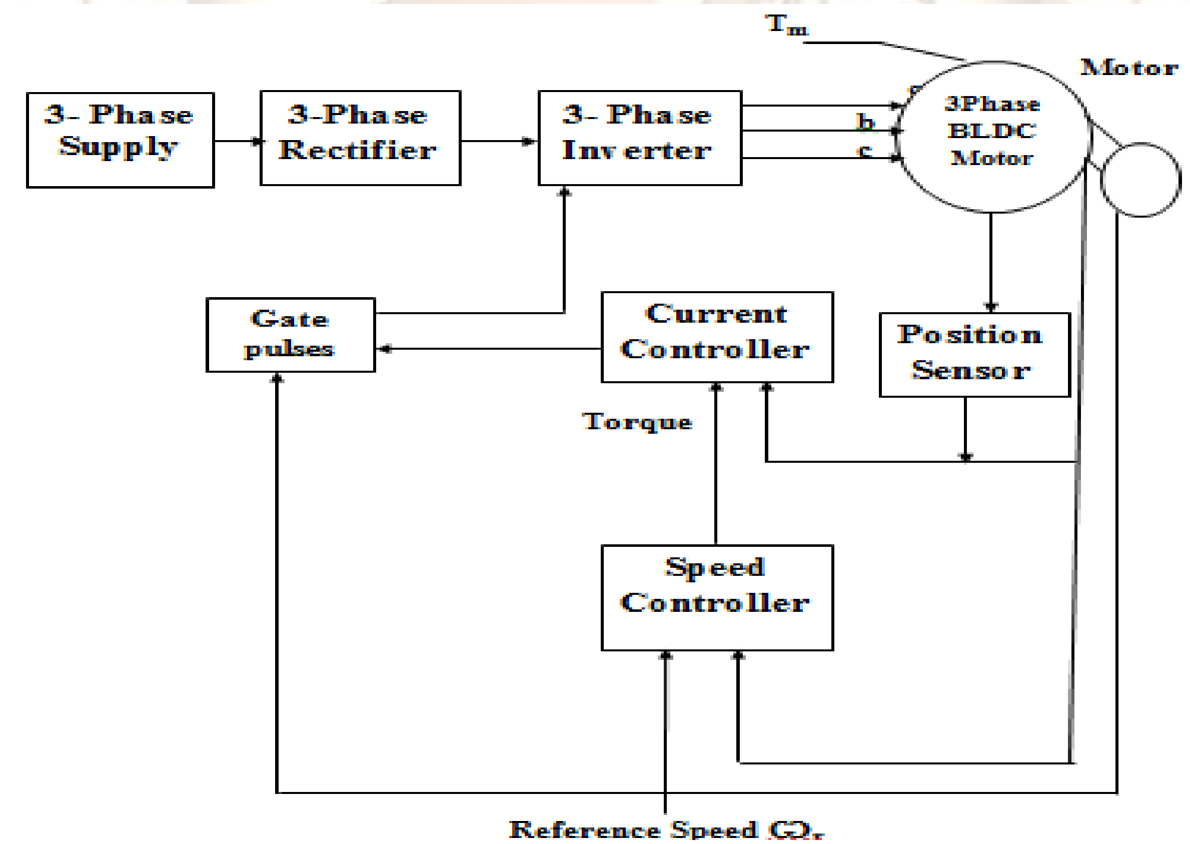

Fig 1 Brushless D.C. Motor drive

3. PROBLEM IDENTIFICATION IN BLDC MOTOR DRIVE

PROBLEM RELATED TO SPEED CONTROL OF BRUSHLESS D.C. MOTOR DRIVE USING SENSORS

1. Low-cost Hall-effect sensors are usually used.
2. Electromagnetic variable reluctance (VR) sensors
3. Accelerometers have been extensively applied to measure motor position and speed.

Hall-effect sensors

These kinds of devices are based on Hall-effect theory, which states that if an electric current- carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers that tends to push them to one side of the conductor. A build-up of charge at the sides of the conductors will balance this magnetic influence producing a measurable voltage between the two sides of the conductor.

To rotate the BLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall-effect sensors embedded into the stator

The connecting principle between the brushless motor and this sensor is reminiscent of the miniaturized magnetic angular encoder based on 3-D Hall sensors. A permanent magnet is fixed at the end of a rotary shaft and the magnetic sensor is placed below, and the magnet creates a magnetic field parallel to the sensor surface. This surface corresponds to the sensitive directions of the magnetic sensor. Three-phase brushless motors need three signals with a phase shift of 120° for control, so a closed-loop regulation may be used to improve the motor performance.

PROBLEMS OCCUR IN SELECTING THE VALUE OF PI CONTROLLER GAIN
SPEED CONTROLLER

The rotor rotation of the BLDC motor, while the motor speed depends only on the amplitude of the applied voltage. The required speed is controlled using a speed controller. The speed controller is implemented as a conventional PI controller.

Proportional Integral Controller Design

The model of PI speed controller is given by,

$$G(s) = K_p + (K_i / s)$$

Where G(S) is the controller transfer function which is torque to error ratio in s-domain, Kp is the proportional gain and Ki is the integral gain. The tuning of these parameters is done using Ziegler Nichols method using the phase and gain Margin specifications. The specifications of the drive application are usually available in terms of percentage overshoot and settling time. The PI parameters are chosen so as to place the poles at appropriate locations to get the desired response.

These parameters are obtained using Ziegler Nichols method which ensures stability. From the dynamic response obtained by simulation, the percentages overshoot Mp and settling time ts which are the measures of Transient behaviors are obtained. The speed loop of the typical BLDC motor under no load condition.

The closed loop transfer function of the system is given by

$$T(s) = (Kp\,S + K_i) / [J\,(s^2 + (B + K_p/J)\,S + (K_i/J))]$$

Where T(S) is the closed loop transfer function and Kp, Ki Are the PI controller parameters, J is the moment of inertia And B is the coefficient of friction.

$$K_p = 2\zeta.\,\omega_n\, J.B$$
$$K_i = J.\omega_n$$

ζ = Damping Ratio, Risetime $= t_r = \frac{(\pi - \Phi)}{(\omega n\sqrt{1-\zeta 2})}$,

Phase Angle = $\boldsymbol{\Phi = \tan^{-1}}(\frac{\sqrt{1-\zeta 2}}{\zeta})$ Maximum Overshoot = $M_p = \mathbf{e}^{\frac{-\zeta\,\pi}{\sqrt{1-\zeta 2}}}$

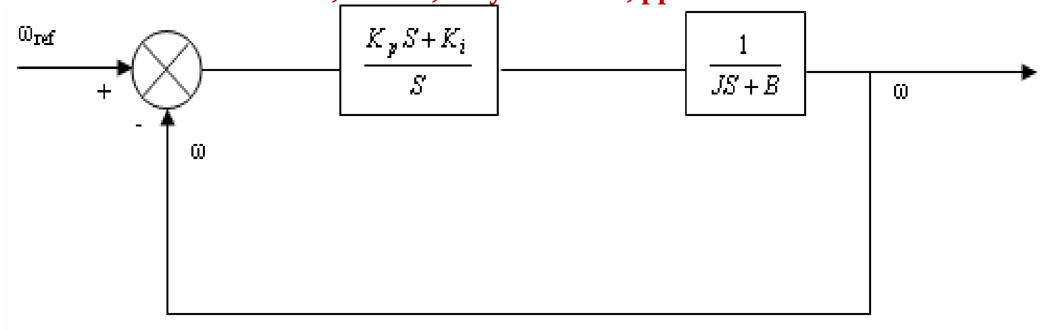

Fig. 2 Speed loop showing the PI controller and BLDC

$S^2 + 2\zeta\omega_n + \omega_n^2 = 0$ (second order system characteristics equation)

$$T(s) = (Kp\,S + K_i)\,/[J(s^2 + (B + K_p/J)S + K_i\,/J)]$$

$$T(s) = G(s).H(s) \quad = \left(\frac{kp\,S+ki}{S}\right).\left(\frac{1}{JS+B}\right)$$

$$= \frac{Kp\,S+Ki}{S\,(JS+B)} \;=\; \frac{Kp\,S+Ki}{J\left(S^2+\left(\frac{B+Kp}{J}\right)S+\left(\frac{Ki}{J}\right)\right)}$$

$$\omega_n = \sqrt{\frac{Ki}{J}}$$

$$2\zeta\omega_n = \frac{B+Kp}{J}$$

$$\zeta = \frac{B+Kp}{2J}\sqrt{\frac{J}{Ki}} = \left(\frac{B+Kp}{2}\right)\sqrt{\frac{1}{J.Ki}}$$

Here,
J = Rotor Inertia of BLDC Motor = 0.087 kg.m^2
B = Viscous Friction of BLDC Motor = 0.005 N.m.s

S. N.	K_i	K_p	ζ	ω_n	Φ	Rise Time t_r	Peak Overshoot M_p
1.	0	0	0	0	0	0	0
2.	10	5	0.085	0.339	85.12	280.71	0.765
3.	10	15	0.254	0.339	75.28	319.38	0.438
4	10	20	0.339	0.339	70.18	344.34	0.323
5.	10	30	0.509	0.339	50.40	444.14	0.159
6.	10	50	0.848	0.339	32.01	823.68	0.0066
7.	10	80	0.356	0.339	0	0	0
8.	30	50	0.489	0.587	60.73	232.14	0.172
9.	50	50	0.379	0.758	67.73	160.05	0.276

Table.1 Compare chart for selecting K_i and Kpvalue.

Note: Proportional control will reduce the steady state error, but at the cost of large overshoot. Furthermore, K_p (Proportional Gain) will never completely eliminate the steady state error. For we need to try integral control. Let implement PI controller and start with a small K_i.

To reduce the settling time, we can increase K_i but by doing this transient response will get worse (i.e. large overshoot).

The effects of increasing each of the controller parameters K_p, K_D and K_i can be summarized as following table2.

S.N	Response	Rise Time	Settling Time	Overshoot	Steady State Error
1.	K_p	Decrease	NT	Increase	Decrease
2.	K_i	Decrease	Increase	Increase	Eliminate

3.	K_D	NT	Decrease	Decrease	NT

Table 2 Controlling parameters K_p, K_D and K_i can be summarized

NT = Not definite trend (i.e Minor Change)

4. METHODOLOGY

MATHEMATICAL MODELING OF THE AC MACHINE

The electrical system dynamics may be described by two voltage equation:

$$v_1 = r_1\, i_1 + p\lambda_1 \quad \text{----------------------- (5)}$$

$$v_2 = r_2\, i_2 + p\lambda_2 \quad \text{----------------------- (6)}$$

Where p is the Heaviside notation for the time differentiation operator d/dt. Assume that the stator flux linkages are linearly related to the currents, the flux linkage λ_1 and λ_2 may be expressed:

$$\lambda_1 = L_{11}\, i_1 + L_{12}\, i_2 + \lambda_{pm1} \quad \text{------------------------ (7)}$$

$$\lambda_2 = L_{21}\, i_1 + L_{22}\, i_2 + \lambda_{pm2} \quad \text{----------------------- (8)}$$

The stator windings are symmetric, i.e. they have the same total self-inductance, resistance, and number of turns. Since the self –inductance is the same for windings, L_{11} and L_{22} in (7) and (8) will denote as L_{ss}. Since the stator windings are tightly wound on highly permeable stator steel, the numerical value of the mutual inductance is nearly equal to the total self-inductance. However, since the magnetic axes are in opposite directions for positive current in each winding, the mutual inductance is negative. A minus sign and the symbol L_m will replace L_{12} and L_{21} in equation no. (7) and (8). The symmetry and configuration of the windings indicate that both have the same permanent–magnet component of flux linkage but with opposite signs. The symbol λ_m will be used for the permanent-magnet flux linkage term.

$$v_1 = r_s i_1 + L_{ss}\, p\, i_1 - L_m\, p\, i_2 + p\lambda_m \quad \text{---------------------- (9)}$$

$$v_2 = r_s i2 - L_{ss}\, p\, i_1 + L_m\, p\, i_2 - p\lambda_m \quad \text{---------------------- (10)}$$

In equation (9) and (10), $p\lambda_m$can be expressed as $\omega_r(d\lambda_m/d\theta_r)$ and represents the no-load or back emf of the motor. The induced voltage due to armature reaction are related to the terms containing L_{ss} and L_m which, when added to the back emf , establish the total induced voltages in the stator windings.

For the mechanical system, the torque developed by the electromagnetic system counters the inertial acceleration torque, the torques due to windage and friction (modeled as being proportional to rotor velocity), and the load torque , i.e.

$$T_e = J_p\omega_r + B\,\omega_r + T_L \quad \text{--------------------- (11)}$$

The interaction of currents in the stator electrical system with the magnetic field of the rotor permanent magnets creates an electromagnetic torque, T_e. The electromagnetic torque may be established by expressing the partial derivative of the co energy w.r.t. position. The resulting expression for the electromagnetic torque is:

$$T_e = (i_1 - i_2)\frac{d\lambda m}{d\theta r} - \frac{dWpm}{d\theta r} \quad \text{--------------------- (12)}$$

Where W_{pm} represented the coupling field energy due to the permanent magnets. Total derivatives because λ_m and W_{pm} are functions only of θ_r. The first term on the right-hand side of equation (12) represents the electromagnetic torque produced by the interaction of electric current in the stator windings with the magnetic field of the rotor permanent magnets. The second term represents a torque due to the attraction between the rotor permanent magnet and the stator steel and acts to drive the rotor to a position having the lowest permanent magnet component of coupling field energy.

This torque hereafter referred to as the cogging torque T_{ec}, ensures that the rotor position of the unexcited motor is such that an electromagnetic torque sufficient for starting is developed when the stator windings are suddenly energized.

The cogging torque does not depend upon the stator currents and is a function only of θ_r. It is incorporated in the state model as a position dependent load torque. The cogging torque is assumed to very sinusoidalw.r.t. Rotor position. The peak value of the cogging torque and the rotor position at which the cogging torque is maximum were measured experimentally for the given four-pole motor. The variation of cogging torque w.r.t. rotor position is not exactly sinusoidal; the only time that the cogging torque is important is during start-up.

In practically, the cogging torques acts to drive the rotor of an unexcited machine to a position such that when the source voltage is suddenly applied, the resulting electromagnetic torque accelerates the rotor in the proper direction. After some algebraic manipulation, (9), (10) and (11) may be expressed in state-model from as:

$$pi_1 = \frac{1}{Lss\ (1-k2)}\left[(v_1 - r_s) + k(v_2 - r_s\, i_2) - (1-k)\,\omega_r \frac{d\lambda m}{d\theta r}\right] \quad \text{-------------(13)}$$

$$pi_2 = \frac{1}{Lss\ (1-k2)}\ [k\ (\nu_1 - r_s i_1\ ) + (\ \nu_2 - r_s\ i_2) + (1\text{-}k)\ \omega_r \frac{d\lambda m}{d\theta r}\ ] \quad \text{--------------(14)}$$

$$p\omega_r = \frac{1}{J}\ (T_e - B\ \omega_r - T_L) \quad \text{------------- (15)}$$

$$p\theta_r = \omega_r \quad \text{--------------- (16)}$$

Where $k = {Lm}/{Lss}$ denotes a coefficient of coupling. In equation (13), (14) and (15), the applied stator voltages ν_1 and ν_2 and the load torque T_L represent inputs variables.
θ_r = electrical rotor position and ω_r= electrical rotor velocity .. i.e.θ_r= (4/2) θ_{rm}=2 θ_{rm} for the 4-pole motor, or θ_r = (P/2) $\theta_{rm}$for a P-pole device. However, the right-hand side of equation (12) must be multiplied by the number of pole pairs. In subsequent computer studies, the electrical rotor velocity ω_r is plotted rather than the actual rotor velocity ω_{rm}.

PERFORMANCE OF BLDC MOTOR
The actual shaft output torque is:

$$T_{load} = T_{em} - T_{losses}$$

Where T_{losses} is the total losses due to friction, windage, and iron losses. Dropping the amplitude signs, we have

$$T_{em} = \frac{mp}{2} \lambda m\ I$$

Speed-torque curve:- The voltage equation can be simplified as

$$V = E + IR$$

Substituting the relations of E -ω_r and T-I, we obtain.

$$\nu = \frac{P}{2}\omega_r\lambda_m + \frac{2R}{mp\lambda m}\ T_{em}$$

$$\omega_r = \frac{2\nu}{p\lambda m} - \frac{4R}{m\,(p\lambda m\,)2}\ T_{em}$$

Fig. 3 Torque-Speed curve is drawn for a constant voltage

Mechanical input
Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J\frac{d}{dt}\omega_r + F\ \omega_r + T_m$$

This mechanical system is included in the motor model.

However if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

Block diagram of BLDC Motor Drive:
This circuit uses the AC7 block of SimPower System library. It models a brushless DC motor drive with a braking chopper for a 3HP motor.
The permanent magnet synchronous motor (with trapezoidal back-EMF) is fed by a three phase inverter, which is built using a Universal Bridge Block.
The speed control loop uses a PI regulator to produce the torque reference for the current control block.

Brushless D.C. Motor Drive (SIMULINK)
Implement brushless DC motor drive using Permanent Magnet Synchronous Motor (PMSM) with trapezoidal back electromotive force (BEMF)

Description:

The high-level schematic shown below is built from six main blocks. The PMSM, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library.

The speed controller, the braking chopper, and the current controller models are specific to the Electric Drives library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation.

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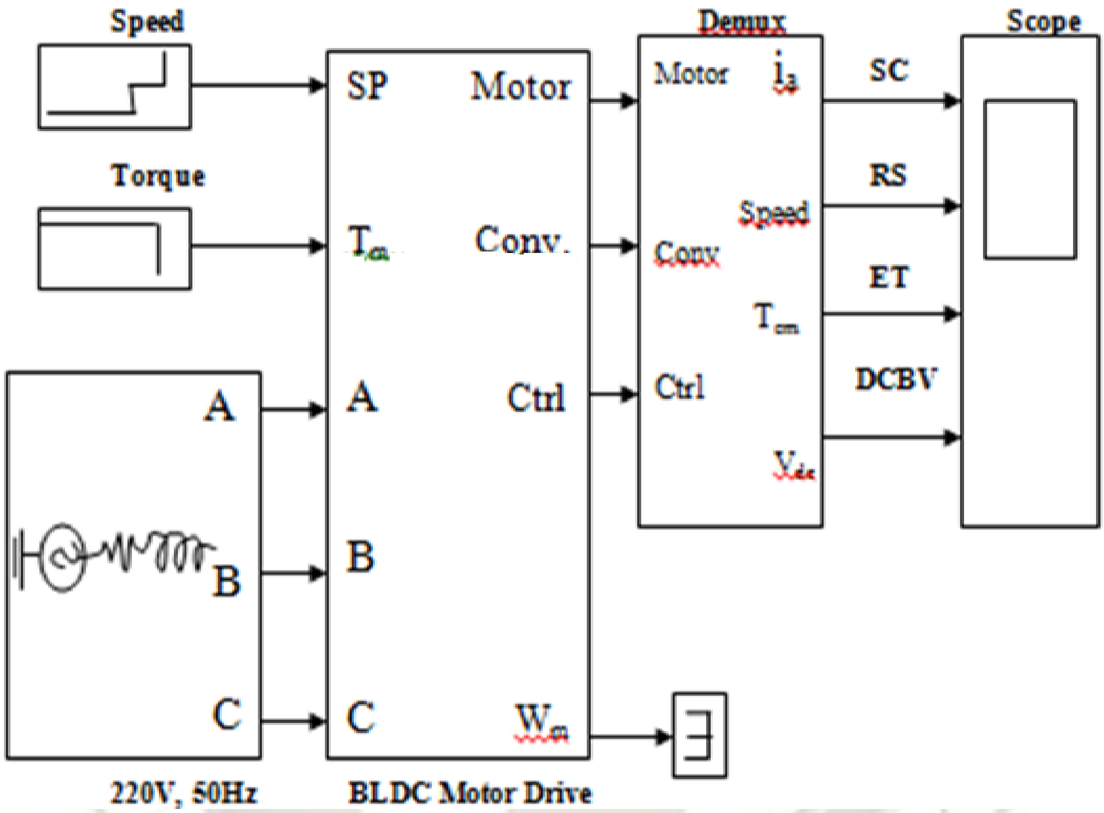

Fig.4Modelling analysis of Brushless Direct Current Motor Drive with MATLAB/SIMULINK.

Here

SC - Stator Current
RS – Rotor Speed
ET – Electromagnetic Torque
DCBV – D.C. Bus Voltage

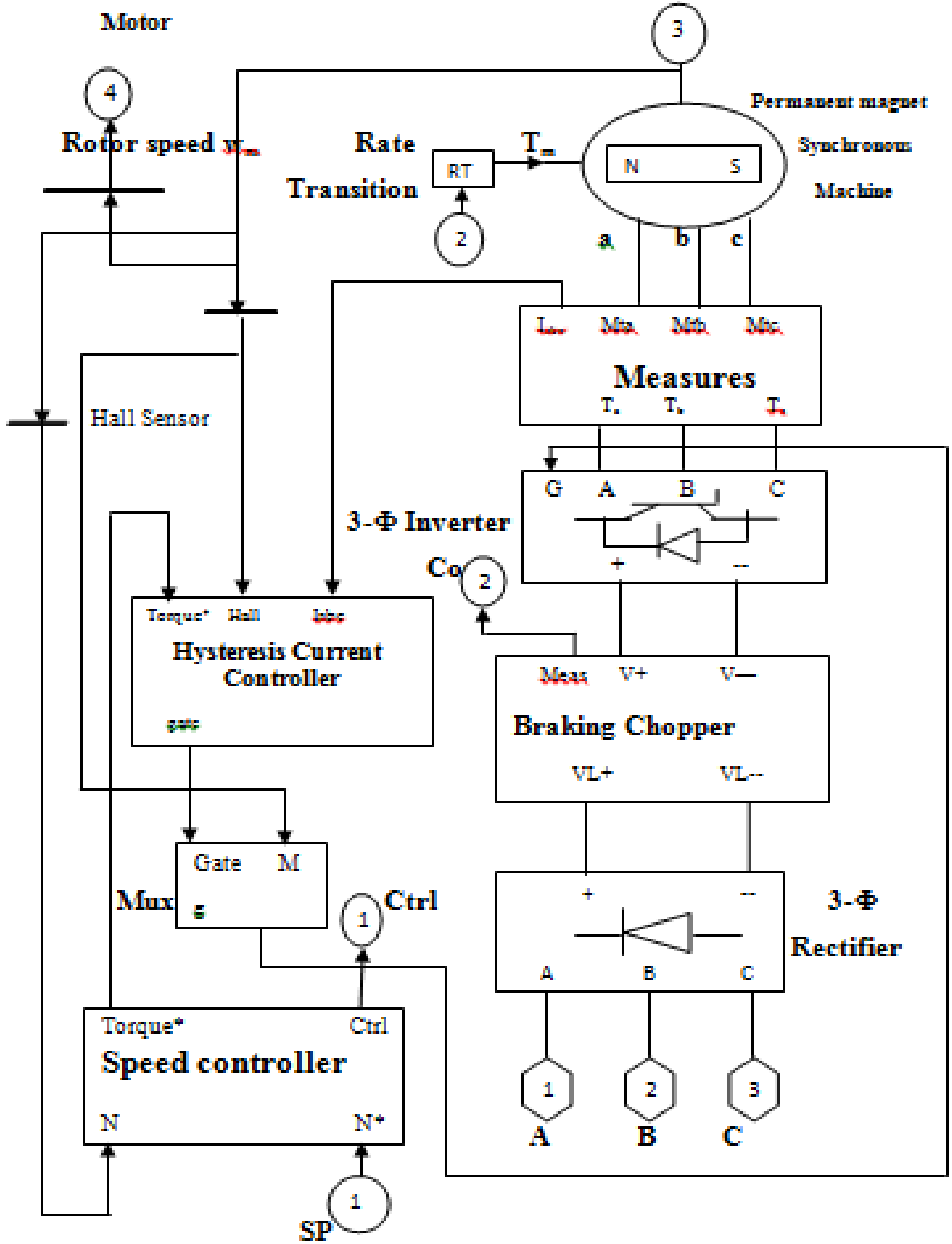

Fig.5Brushless DC Motor Drive

Speed Controller

The speed controller is based on a PI controller, shown above. The output of this controller is a torque set point applied to the current controller block.

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Vol. 2, Issue 3, May-Jun 2012, pp.2868-2884

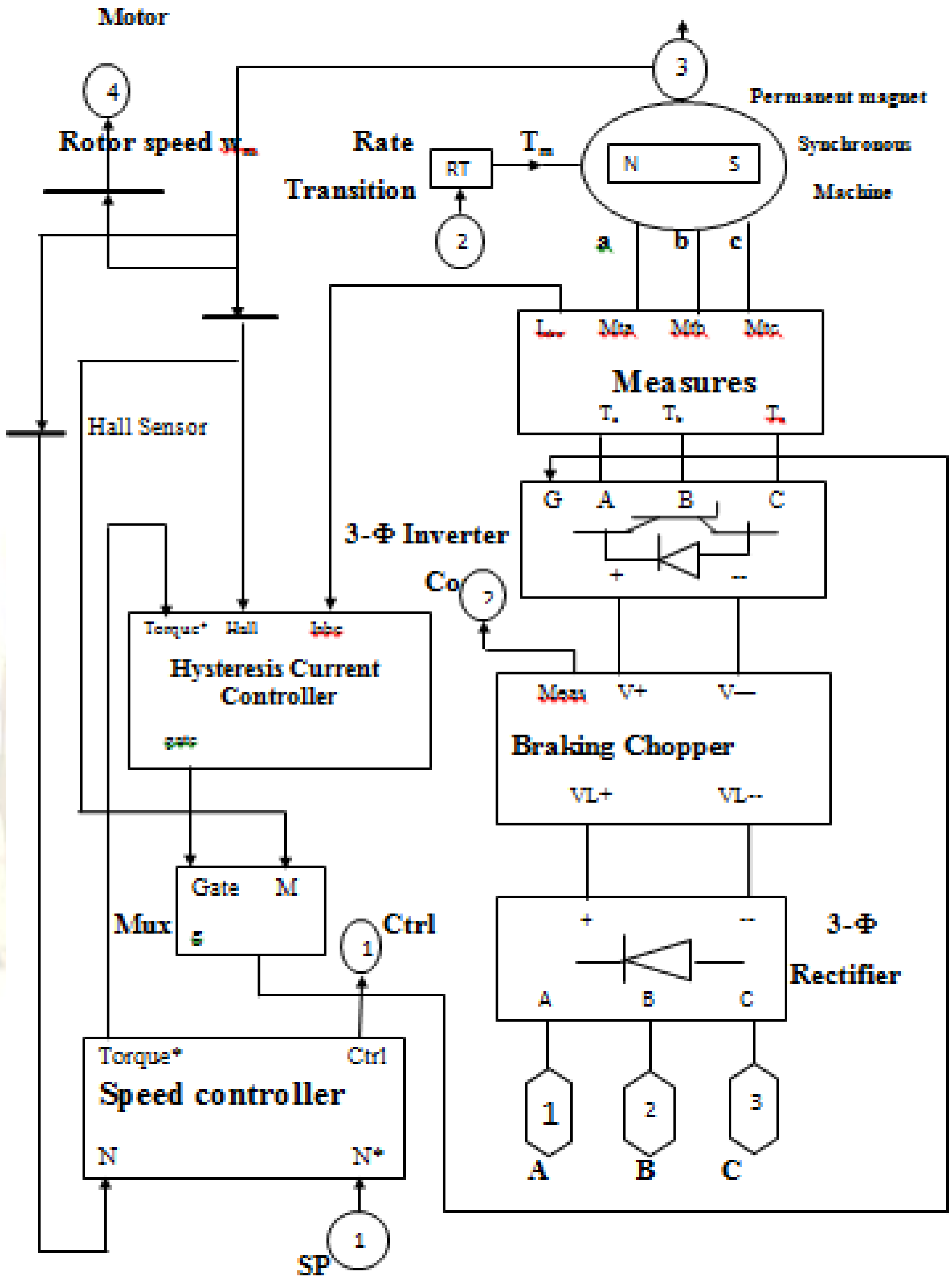


Fig 6 Speed Controller

Current Controllers

In the BLDC motor drive, duty cycle controlled voltage PWM technique and hysteresis current control technique can be regarded as the main current control strategies.

In this thesis bipolar hysteresis current control is used for obtaining the fast dynamic responses during transient states.

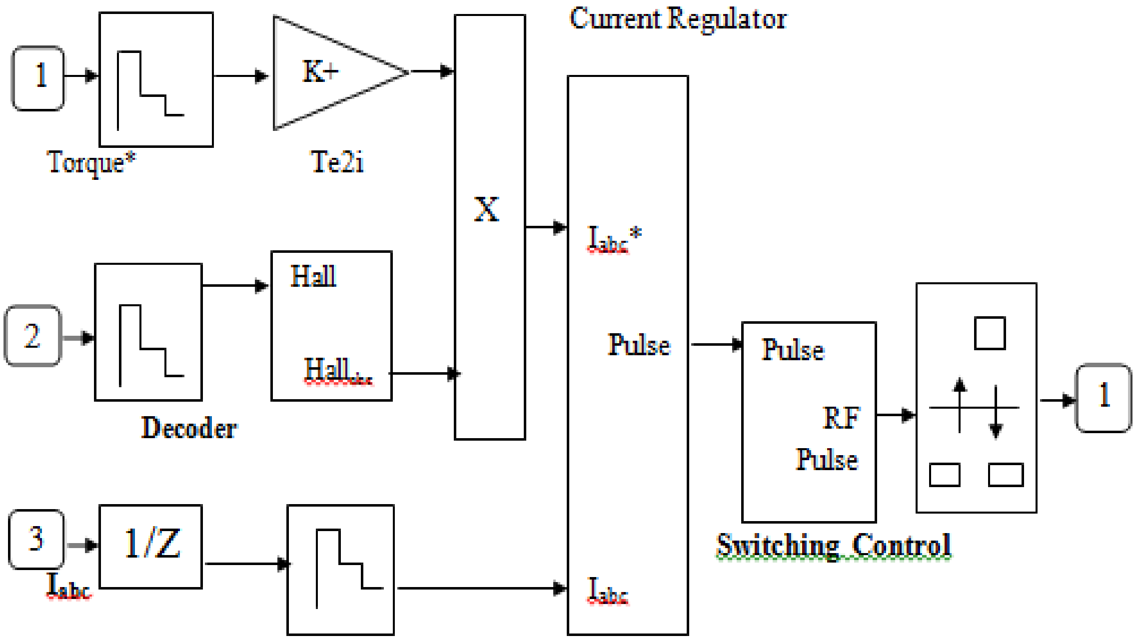
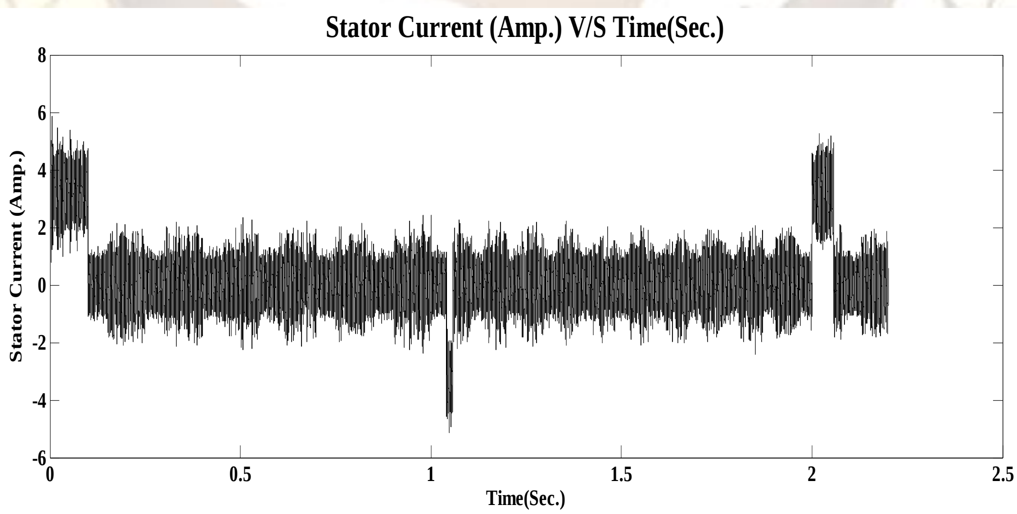


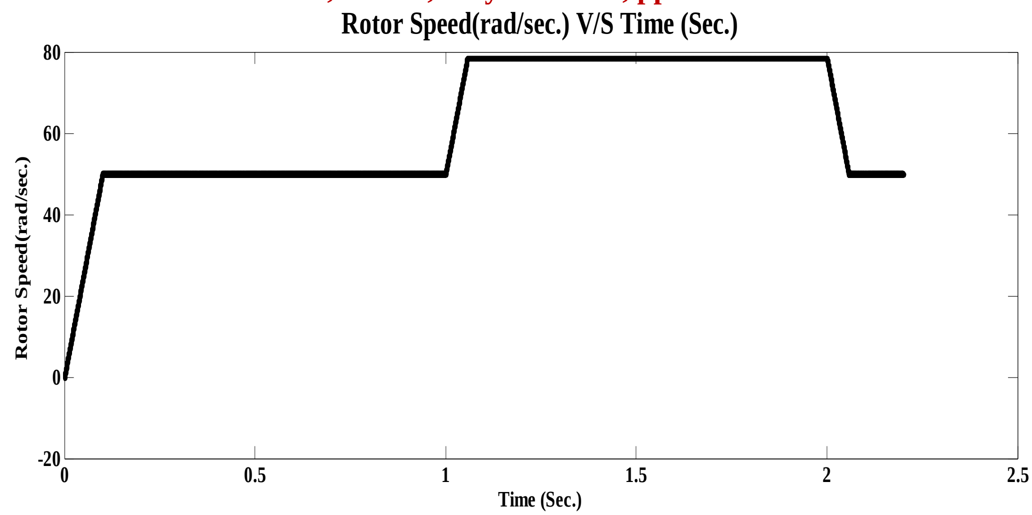
Fig.7 Current Controller

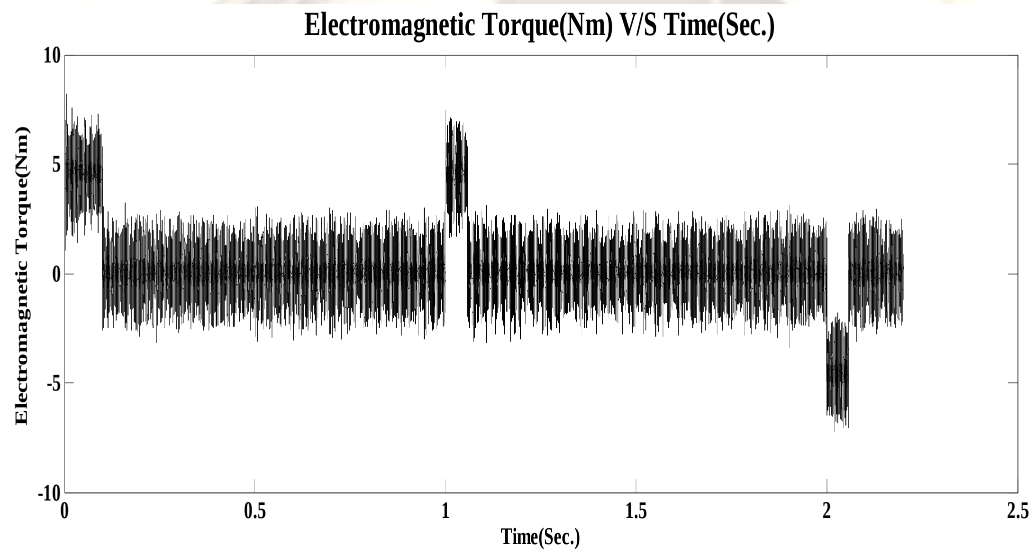
5. RESULTS and CONCLUSION

Case: I For without Torque load Condition (Speed and Torque)

Torque Parameters:	**Time (sec.)**	**0**	**1**	**2**
	Torque (Nm)	**0**	**0**	**0**
Speed Parameters	**Speed (rad/sec)**	**50**	**78.5**	**50**







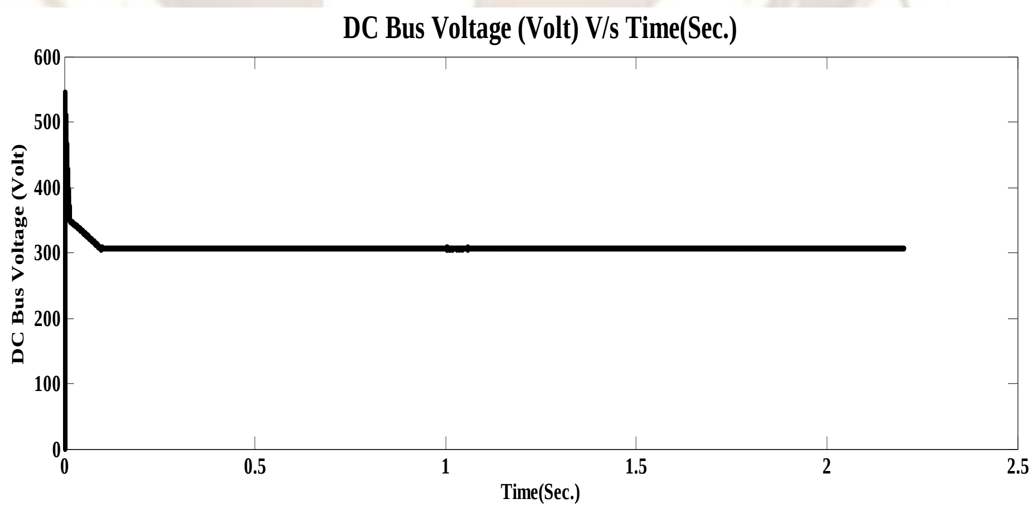


Fig 8 Wave forn analysis for Without Torque Condition (Speed and Torque)

Stator Current of BLDC Motor

This graph represents the stator current (i_a in Amp) vs time (in sec.) of Brushless Dc Motor. Stator current waveform is not smooth because some harmonics are present in input.

Rotor Speed of BLDC Motor

This graph represents the rotor speed (in rpm) vs time (in sec) of BLDC motor.

Speed of themotor is varied in between Rated Speed 78.5 rad/sec. at 0 sec but without Torque. BLDC Motor is 8poles Motor and frequency is 50 Hz, then

Speed(N) = (120*frequency) / Numbers of poles.

Ꞷm = 2π* N

Electromagnetic Torque of BLDC motor

As shown in the following figure, the speed precisely follows the acceleration ramp. At t = 0.2 s, the nominal load torque is applied 1.4 Nm to the motor. At t = 1 s, the speed set point is changed to 0 rpm. The speed increases to 0 rpm. At t = 1.2 s., the mechanical load passes from 0 N.m.

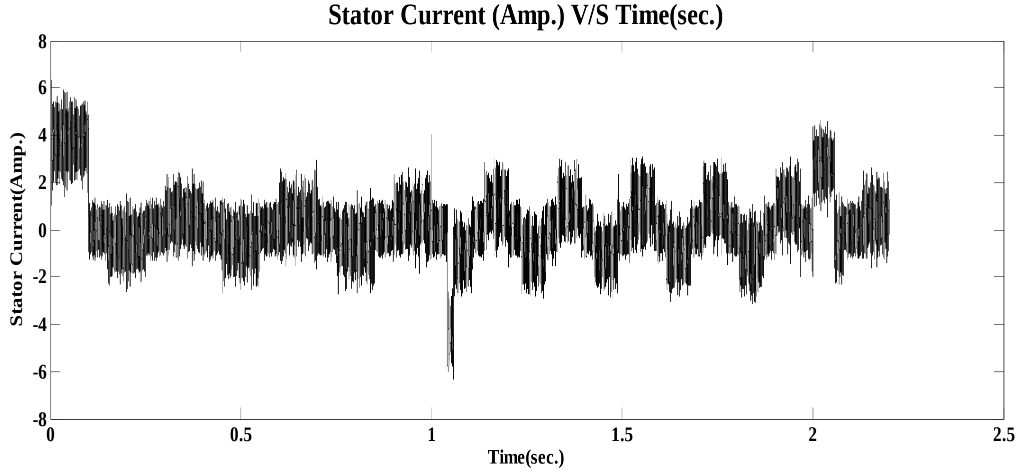
DC Bus voltage of BLDC Motor

This graph represents the variation of dc bus voltage (in volts) with respect to time (in sec.). This D.C. bus voltage is obtained from Three- phase rectifier circuits.

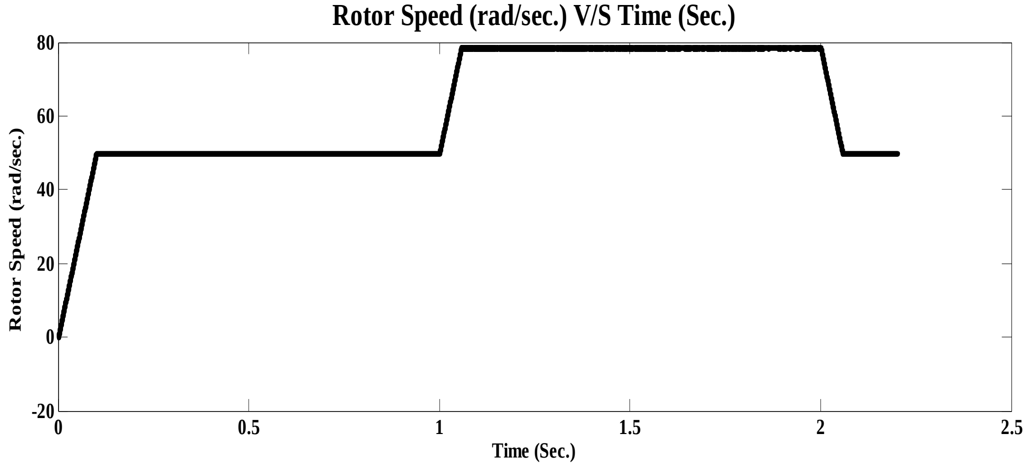
Case: II For Transient load Condition (Speed and Torque)

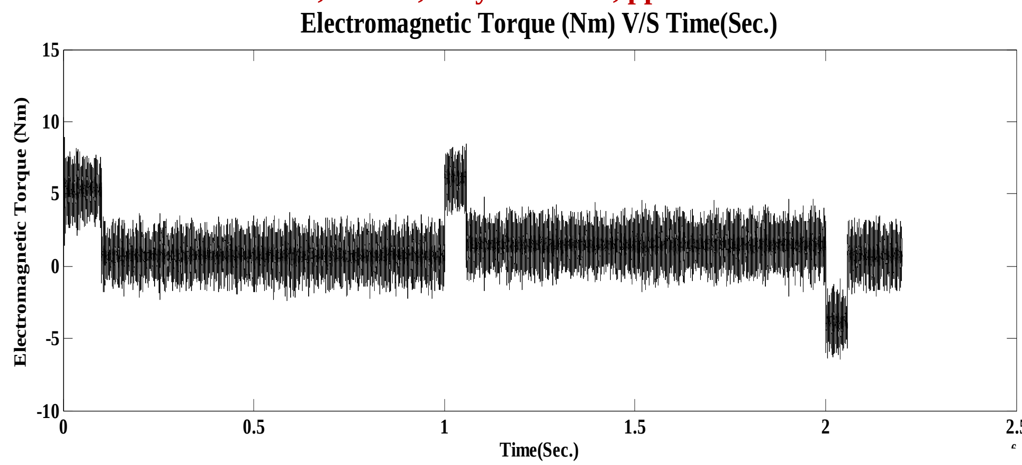
Torque Parameters:	**Time (sec.)**		**0**	**1**	**2**
	Torque (Nm)		**0.7**	**1.4**	**0.7**
Speed Parameters	**Speed (rad/sec)**	**50**	**78.5**	**50**	

Stator Current (Amp.) V/S Time(sec.)



Rotor Speed (rad/sec.) V/S Time (Sec.)





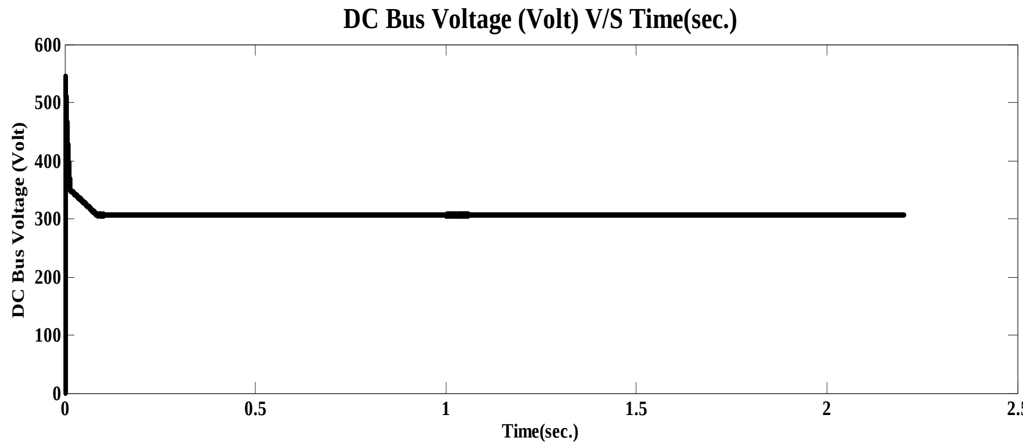
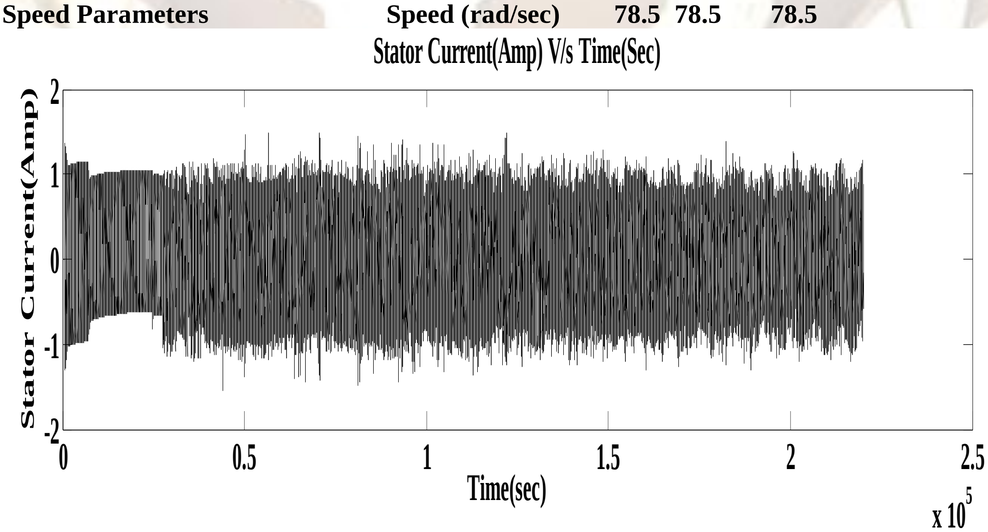


Fig 9 Waveform for Transient load Condition (Speed and Torque)

Case: IIIKi=0 and Kp=0,
For Transient load Condition (Speed and Torque)

Torque Parameters:	**Time (sec.)**		**0**	**1**	**2**
	Torque (Nm)		**0.7**	**1.4**	**0.7**
Speed Parameters	**Speed (rad/sec)**	**78.5**	**78.5**	**78.5**	



When proportional controller gain or Integral controller gain is zero (absence of PI cont transient load conditions following waveforms are obtained.

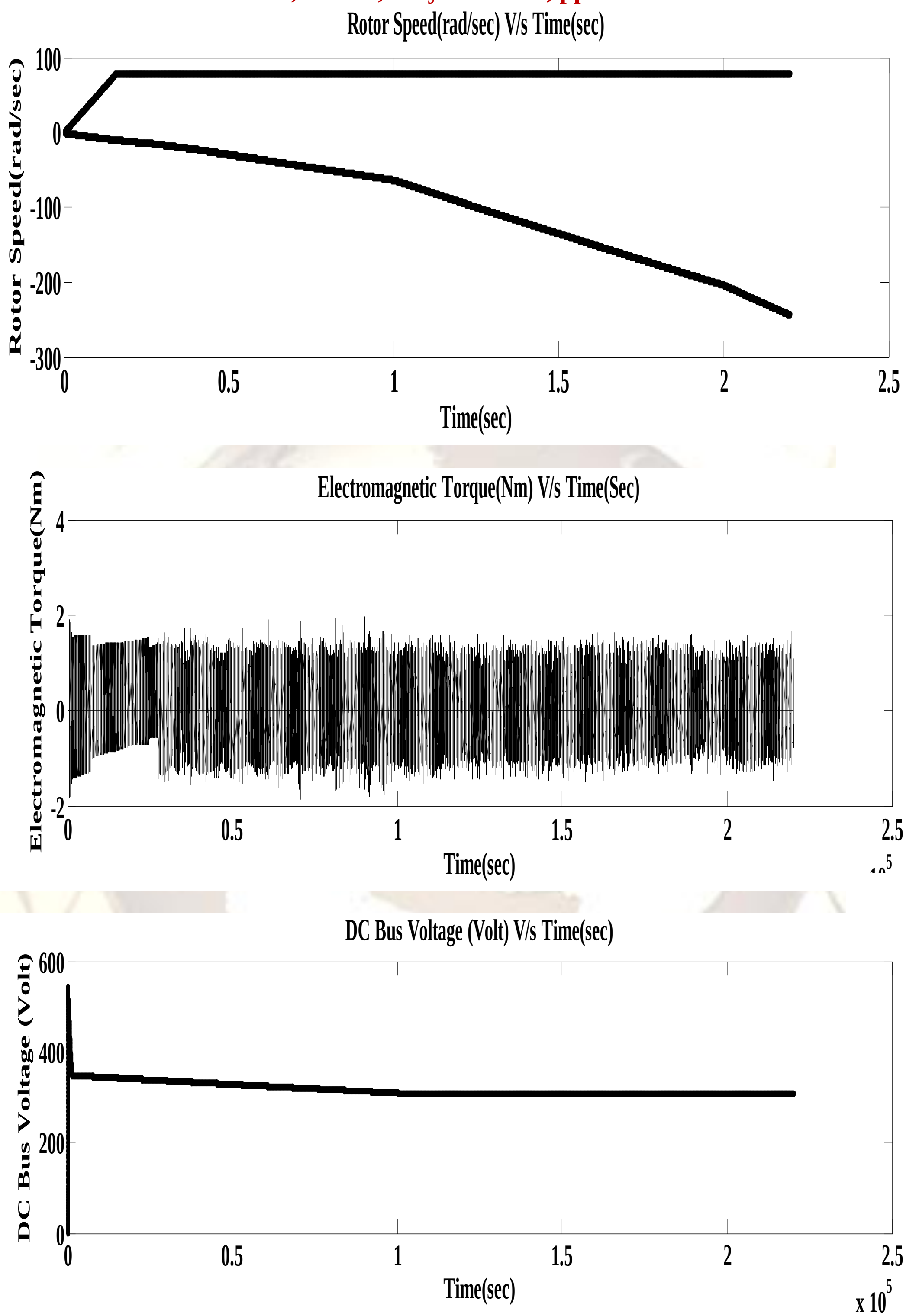
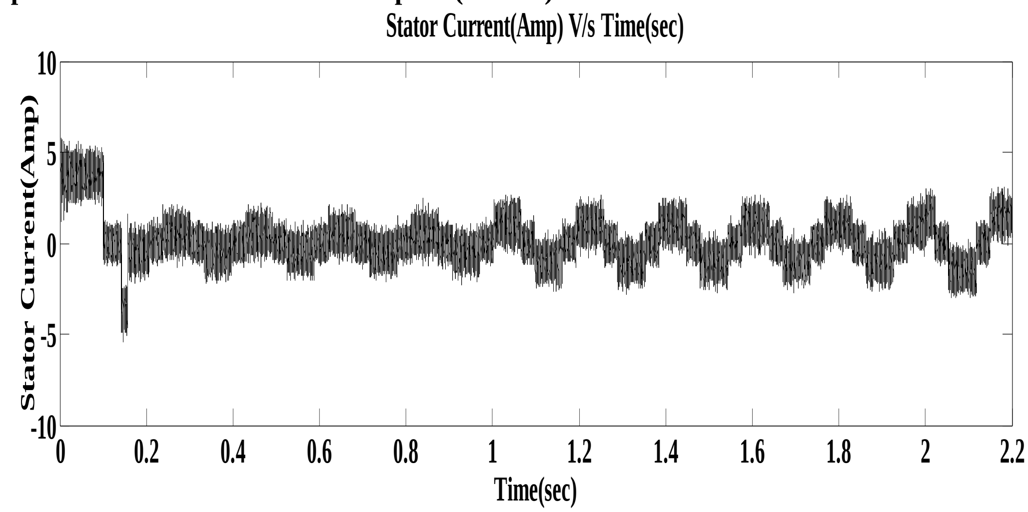


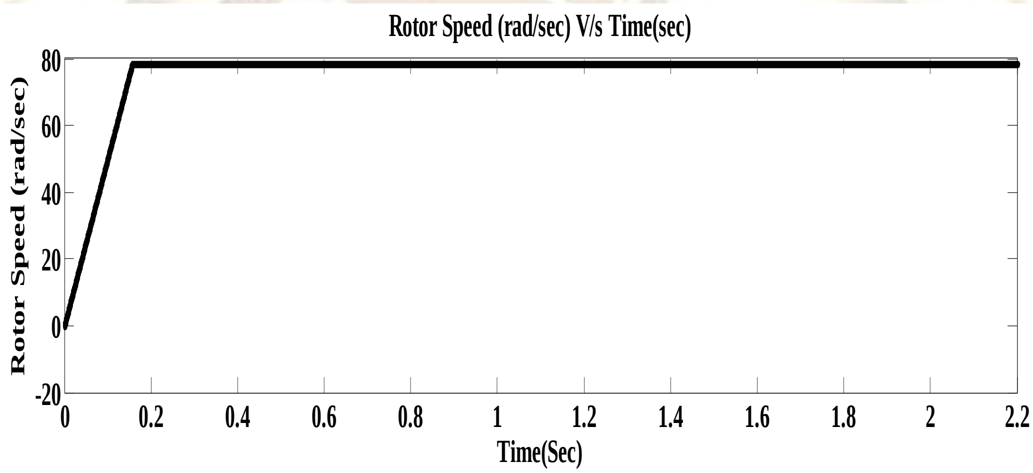
Fig 10 Waveform for analysis for PI controller gain at K_i&K_p zero

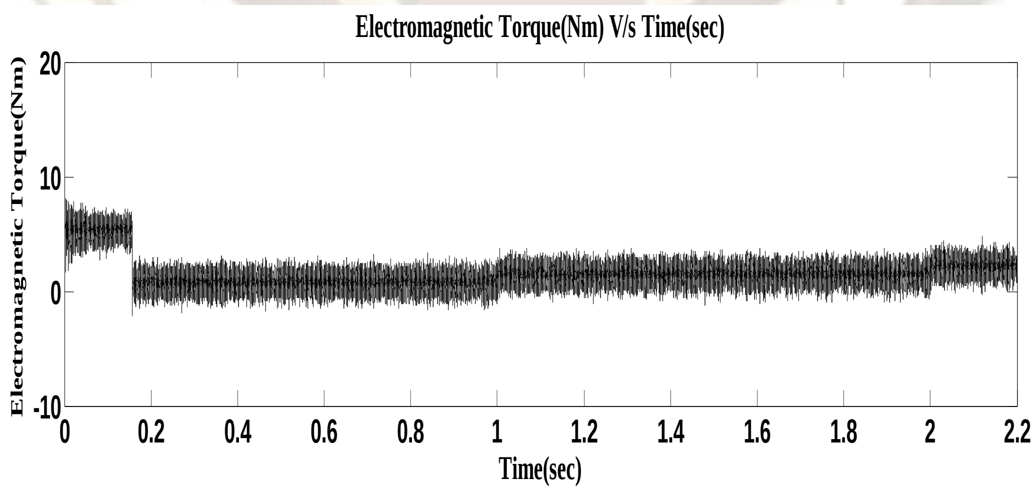
Case: IV Ki=10 and Kp=50,

For Transient load Condition (Speed and Torque)

Torque Parameters:	**Time (sec.)**		**0**	**1**	**2**
	Torque (Nm)		**0.7**	**1.4**	**0.7**
Speed Parameters	**Speed (rad/sec)**	**78.5**	**78.5**	**78.5**	







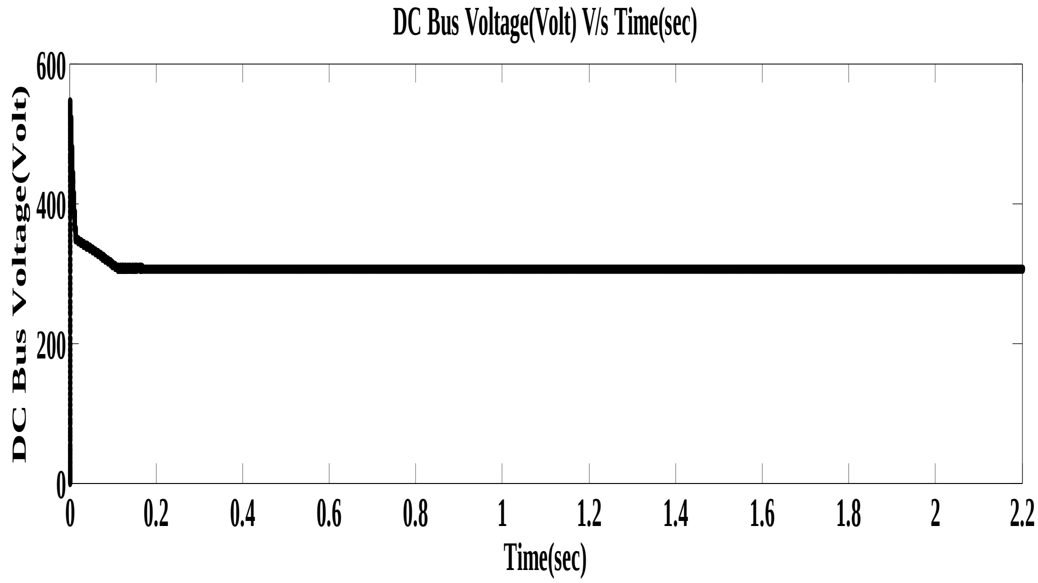


Fig. 11 Waveform for analysis PI controller gain for Transient load Condition (Speed &Torque)

From varies values of Ki and Kp minimum peak overshoot and maximum rise time is obtained at a value of Ki=10 and Kp=50.

Hence we obtained following waveform at transient condition.

Therefore, we can conclude that in presence of Ki and Kp or PI controller, we obtained a better and stable stator current vs time, rotor speed vs time, electromagnetic torque vs time and DC bus voltage vs time curve.

CONCLUSION

In this thesis, a mathematical model of brushless DC motor is developed. The simulation of the brushless DC motor was done using the software package MATLAB/SIMULINK.

In this thesis a review of position control using Hall sensor methods for BLDC motors has been presented. It is obvious that the control for BLDC motors using position sensors, such as shaft encoders, resolvers or Hall-effect probes, can be improved by means of the elimination of these sensors to further reduce cost and increase reliability.

In this thesis we have done result analysis and found results in different load conditions. We have also analyzed the steady state condition and transient condition. The steady state condition was found to be very close to the transient condition.

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