PROPORTIONAL INTEGRAL &DERIVATIVE CONTROLLER FOR BLDC MOTOR

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ABSTRACT

The Brushless DC (BLDC) motors are one of the electrical drives that are now widely being used in industrial applications and are rapidly gaining popularity, due to their high efficiency, good dynamic response, high power density, high reliability, and maintenance-free reputation. These motors are generally controlled using a three phase full bridge pulse width modulated (PWM) voltage source inverter. For starting of the motor, for providing proper commutation sequence and to turn on the power devices in the inverter bridge the rotor position sensors required. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. To achieve desired level of performance the motor requires suitable speed controllers. In case of industrial drives, the speed control is usually achieved by using Proportional-Integral-Derivative (PID) controller. PID controllers are widely used in the industries due to their simple control structure and ease of implementation. This paper presents a proportional-integral-derivative (PID) controller for the speed control of BLDC motor. This work mainly focuses on the design of the speed controller for the closed loop operation of BLDC motor. The PID speed Controller for the BLDC motor drive is designed and simulated using MATLAB/SIMULINK software package. Thus a speed controller has been designed successfully for closed loop operation of the BLDC motor and the motor runs very closed to the reference speed.

Index Terms—Brushless DC (BLDC) motor, three phase full bridge pulse width modulated (PWM) inverter, rotor position sensor, and Proportional-Integral-Derivative (PID) controller.

INTRODUCTION

Since the late 1980's new design concept of permanent magnet brushless motors has been developed [1]. The permanent magnet brushless motor can be classified upon to the back-EMF waveform, where it can be operated in either brushless AC (BLAC) or brushless DC (BLDC) modes. Usually the BLAC motors have a sinusoidal back EMF waveform and BLDC motors have a trapezoidal back EMF. BLAC motors with sinusoidal back-EMF waveform are called as permanent magnet synchronous motors (PMSM). The Brushless DC Motor (BLDC) motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal back Electro Motive Force (EMF) waveform shape. The PMSM is very similar to the standard wound rotor synchronous machine except that the PMSM has no damper windings and excitation is provided by a permanent magnet instead of a field winding [2]. The PMSM has a sinusoidal back EMF and requires sinusoidal stator currents to produce constant torque while the BLDC motor has a trapezoidal back EMF and requires rectangular stator currents to produce constant torque.

Compared to conventional DC motors and induction motors, BLDC motors have many advantages and few disadvantages [3]. Comparing BLDC motors with DC motors, the DC motor have high starting torque capability, smooth speed control and the ability to control their torque and flux easily and independently. In the DC motor, the power losses occur mainly in the rotor which limits the heat transfer and consequently the armature winding current density, while in BLDC motor the power losses are practically all in the stator where heat can be easily transferred through the frame, or cooling systems can be used specially in large machines. Commutation of brushless DC motor to supply power from DC source is performed with power electronic inverter rather than mechanical brushes. This enormously improves the reliability of the system over brush DC motors. In addition it reduces the system maintenance cost, and creates clean and safer working system environment. There is no brush; there is no contamination and residual on the bearings. Also there is no arcing associated with brushes; therefore BLDC motors are safer to work in condition where there exits danger of explosive and wider contact with fluid. Brushless DC motor is much quieter both electrically and audibly during operation. In general the induction motor has many advantages as: their simplest construction, simple maintenance, low price and reliability. Furthermore, the disadvantages of induction machines make the BLDC motors more efficient to use and become more attractive option than induction motors. Some of the disadvantages of induction machines are poor dynamic characteristics, lower torque at lower speeds and lower efficiency.

BLDC motor control system mainly comprises of DC voltage source, power electronics inverter, rotor position sensor, and a controller. It is known that induction AC motors and conventional DC motors can run by just connecting them to AC or DC source of power supplies directly without any information about the rotor position. However, BLDC motor control systems need rotor position information during operation. Commutation of brushless DC motor to supply power from DC source is performed with power electronic inverter rather than mechanical brushes. The rotor position information is used to perform electronic commutations through power electronic inverter. In order to obtain the rotor pole position either mechanical or electronic hardware sensor is used [4].

The rotor position sensor is selected depending on the application type, investment-cost, and system environment. Mechanical rotor position sensor provides accurate rotor position information than electronic sensor. This system is called Mechanical sensor control of BLDC motor or it is usually referred to Sensor Control of BLDC motor. However, the cost of mechanical rotor position sensors like encoder, tacho-meter, resolver, and Hall sensor are expensive. Thus, investment cost of mechanical sensor control of BLDC motor is expensive than electronic sensor control of BLDC motor. Therefore in the case of low-budgetBLDC motor applications electronic sensors are preferred over mechanical rotor position sensor.

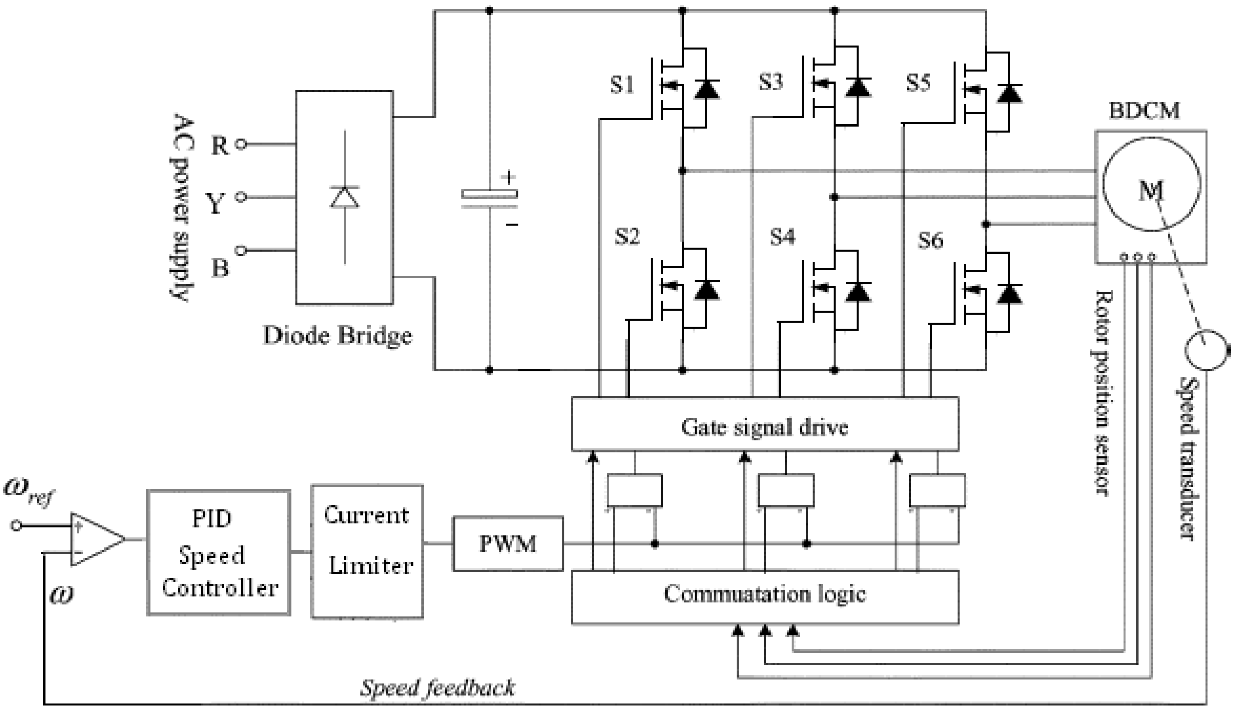


Fig. 1. Functional block diagram of the proposed system.

PROPOSED BLDC MOTOR DRIVE SYSTEMUSING PID CONTROLLER

The overview of the proposed speed control of BLDC motor using a Proportional plus Integral plus Derivative (PID) controller [5] is shown in Fig. 1. Because the controller must direct the rotor rotation, the controller needs some means of determining the rotor's orientation/position relative to the stator coils. This is done by Hall Effect sensors to directly measure the rotor's position. The controller contains 3 bi-directional drivers to drive high-current DC power, which are controlled by a logic circuit.

Control strategies for three-phase BLDC machines are typically implemented using a power converter made of insulated-gate bipolar transistors (IGBTs) or MOSFETs [6]. Electronic commutation of BLDC motor is executed with power electronic semiconductor hardware called Inverters to supply power to the stator coils. Here the 3-phase full bridge Pulse Width Modulated Voltage Source Inverter (VSI) is employed. The 3-phase VSI has three arms, where each of the arms has upper and lower part made of MOSFET switch. Fig. 1.shows inverter switches from S1 to S6. Process of switching on and switching off the inverter arms with a predefined patter or sequence based on the rotor position information interpreted from

Hall Effect sensor, therefore, power will reach to the desired stator coils of the motor. Hence current passes through two of the coils out of three stators.

Speed, torque, and phase currents/voltage are important variables in speed control of BLDC machine. In controlling the speed of BLDC motor the system is closed-loop where actual speed is the feedback parameter that is obtained from the speed transducer. A single stage PID controller consisting of a speed loop has been used for the closed loop drivesystem. PID is simplest and famous controller in Industry and Automation for motor application. The purpose of the system controller is to minimize the error between the reference speed and the feedback speed. In addition, it improves dynamic response and behavior of the system.The function of the current limiter is to maintain the motor phase currents at their desired constant value for each 120° interval that a particular phase is energized. The current is limited by controlling the switch duty cycle to ensure that device current ratings and the motor current rating are not exceeded, especially during start-up conditions or low speed operation. The amount of current ripple is controlled by the switching frequency of a PWM waveform.The gate driver is a drive circuitry which controls the current flow through the MOSFET switches. Hence the current flow to motor windings is also controlled. This includes the direction and magnitude of the current flow.

ROTOR POSITION SENSORSAND ELECTRONIC COMMUTATION

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. 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. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. Fig. 2. shows an example of Hall sensor signals with respect to back EMF and the phase current. Fig. 3.shows the switching sequence that should be followed with respect to the Hall sensors.

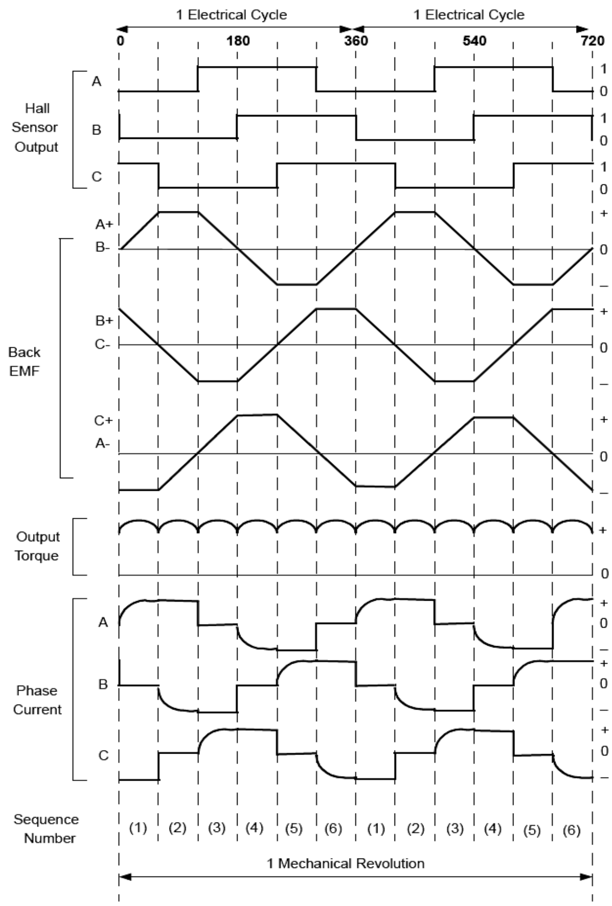


Fig. 2. Hall Sensor Signal, Back EMF, Output Torque and Phase Current.

Sensor-less control of brushless dc motor in general and the back EMF method in particular has drawbacks in estimating the rotor position at very low speed as the value of the back EMF signal generated from the stator coil is very small to detect the rotor position. The rotor position information is not available at standstill as the values of generated back EMF is zero. Therefore Hall Effect sensor is employed here. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor performance.

Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition.Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor as the rotor moves to catch up with the stator field. Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. In synchronous, with every 60 electrical degrees, the phase current switching should be updated. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by

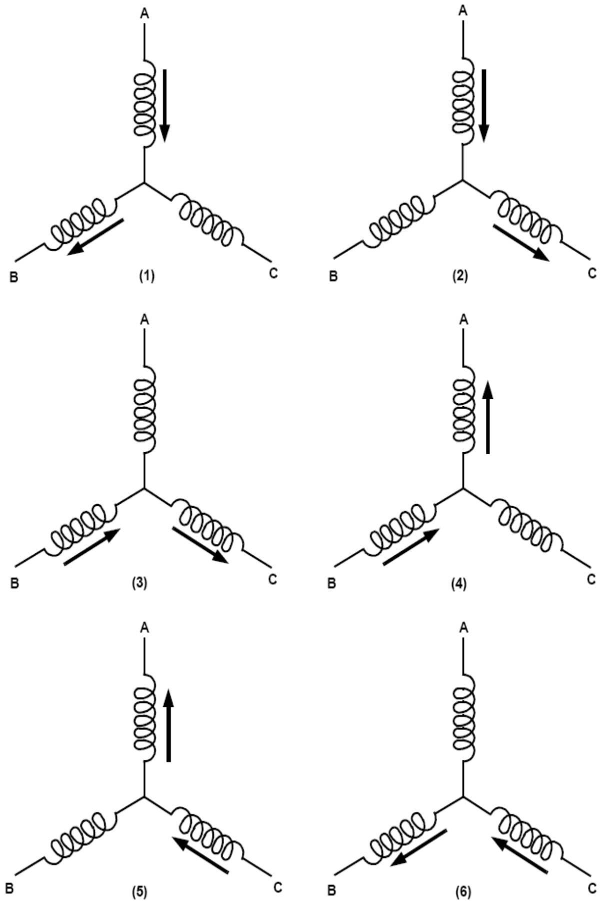


Fig. 3. Winding energizing sequence with respect to the Hall Sensor.

the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles/rotations equals the rotor pole pairs. Table I shows the sequence in which the power switches should be switched based on the Hall sensor outputs [7].

TABLE I

'ELECTRONIC COMMUTATION' BASED ON THE HALL-EFFECT SENSOR SIGNALS

Hall Signals			*Conducting switches*					
H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
0	0	0	0	0	0	0	0	0

0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0

DESIGNOF PID CONTROLLER

In practice, the design of the BLDC motor servo system usually requires time consuming complex process such as model, devise of control Scheme, simulation and parameters tuning. Hence in this paper a simple PID controller based speed control has been proposed for BLDC motor. The PID controller is highly suitable for the linear motor control [8].The PID controller is the most common form of feedback. It was an essential element of early governors and it became the standard tool when process control emerged in the 1940s. In process control today, more than 95% of the control loops are of PID type, most. PID controllers are today found in all areas where control is used. PID control is an important ingredient of a distributed control system. The controllers are also embedded in many special purpose control systems. PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing.

In spite of developed modern control techniques like fuzzy logic controllers or neural networks controllers, PID controllers constitute an important part at industrial control systems so any improvement in PID design and implementation methodology has a serious potential to be used at industrial engineering applications [9]. At industrial applications the PID controllers are preferred widespread due to its robust characteristics against changes at the system model. There is another reason why this project using PID controller instead another method. The first is the three terms are reasonable intuitive, allowing a no specialist grasp the essentials of the controller's action. Second, PID has a long history, dating back to a pre-digital, even pre-electronic period and lastly the introduction of digital control has enhanced PID's capabilities. In general the advantages of PID controller can be summarized as follows:

1. PID controllers do not require advanced mathematics to design.
2. It can be easily tuned unlike other complicated algorithms based on optimal control theory.

A. PID Control Action

In its basic form, PID involves three mathematical control functions working together: Proportional-Integral-Derivative. The most important of these, Proportional Control, determines the magnitude of the difference between the "set point" and the "process variable" (known as "error"), and then applies appropriate proportional changes to the "control variable" to eliminate "error". Many control systems will, in fact, work quite well with only Proportional Control. Integral Control examines the offset of "setpoint" and the "process variable" over time and corrects it when and if necessary. Derivative Control monitors the rate of change of the "process variable" and consequently makes changes to the "output variable" to accommodate unusual changes.

$$u(t) = K_p \left\{ e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right\} \quad (1)$$

Where, e(t) = Set point Measurement(t) is the error signal, and Kp, Ki, Kd are constant that are used to tune the PID control loop.Kp: Proportional Gain - Larger Kp typically means faster response since the larger the error, the larger the feedback to compensate. Ki: Integral Gain - Larger Ki implies steady state errors are eliminated quicker. Kd: Derivative Gain - Larger Kd decreases overshoot, but slows down transient response.

The proportional term makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by constant Kp called the proportional gain. The proportional term is given is given by,

$$P_{out=} K_p\, e(t) \quad (2)$$

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously.

$$I_{out} = K_i \int_0^t e(t)dt \quad (3)$$

The derivative term slows the rate of change of the controller output. Derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability.

$$D_{out} = K_d \frac{de(t)}{dt} \quad (4)$$

B. PID Tuning

Tuning a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. The process of determining the values of these parameters is known as PID Tuning. If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e. its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Instability is caused by excess gain, particularly in the presence of significant lag. Generally, stability of response is required and the process must not oscillate for any combination of process conditions and set points, though sometimes marginal stability (bounded oscillation) is acceptable or desired.

The trial and error method of loop tuning is employed in this project for the design of PID speed controller. This method is crude but could help in getting an overview of what the PID parameters could be like and their effects on the whole system model.

In this tuning method: First set the Ki and Kd values to zero. Increase the Kp until the output of the loop oscillates. Then increase Ki until oscillation stops. Finally, increase Kd until the loop is acceptably quick to reach its reference. A fast PID loop tuning usually overshoots slightly to reach the set point more quickly; however, some systems cannot accept overshoot. The effect of increasing the PID parameters is listed below in the Table II.

TABLE II

EFFECT OF INCREASING THEPIDPARAMETERS

Parameter	*Rise Time*	*Overshoot*	*Settling Time*	*Steady State Error*
K_p	Decreases	Increases	Small Change	Decreases
K_i	Decreases	Increases	Increases	Eliminate
K_d	Small Change	Decreases	Decreases	Small Change

C. Implementation of PID Speed Controller

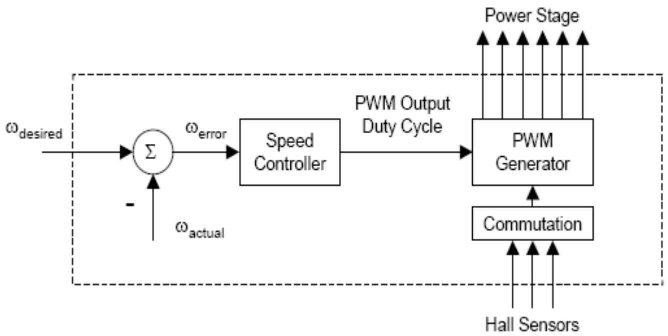


Fig. 4. Implementation of PID Speed Controller.

Fig. 4. shows the implementation of PID speed controller in the speed control of BLDC motor drive system [10]. The speed can be controlled in a closed loop by measuring the actual speed of the motor. The error in the set speed and actual speed is calculated. The PID speed controller is used to amplify the speed error and dynamically adjust the PWM duty cycle.

SIMULATIONUSING MATLAB

The closed loop speed control of a BLDC motor using PID controller is simulated using MATLAB 7.9 software package based on the Simulation Circuit as shown in Fig. 6.The test parameters of the motor taken for simulation are given below.

TABLE III

BLDC MOTOR SPECIFICATIONS

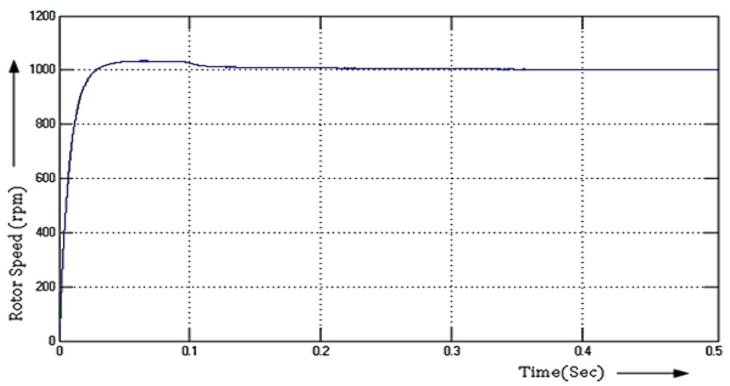
Motor Parameters	*Values*
Rated power	1 KW
No. of phases	3
Rated voltage	400 V dc
Stator resistance/phase	2.875 Ω
Stator Inductance/phase	0.0085 H
Moment of Inertia	0.0008 Kg-m/sec^2
Rated speed	3000 rpm

The calculated gains of PID controller are provided in Table IV. The simulation results for speed reference input of 1000 rpm with the calculated PID tuning parameters are shown in Fig. 5.

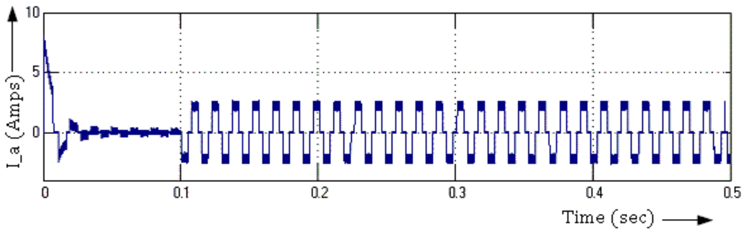
TABLE IV

PIDTUNING PARAMETERS

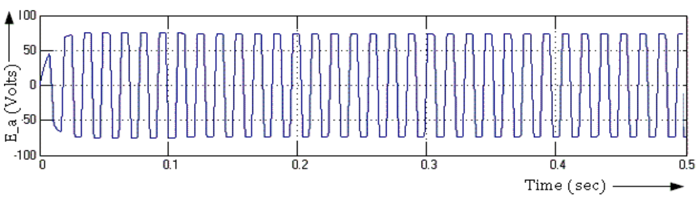
PID PARAMETERS		
K_p	K_i	K_d
40	225	0.3



(a) Rotor Speed vs. Time.



(b) Phase Current Waveform for Phase-A.



(c) Back EMF Waveform for Phase-A.

Fig. 5.Simulation Results.

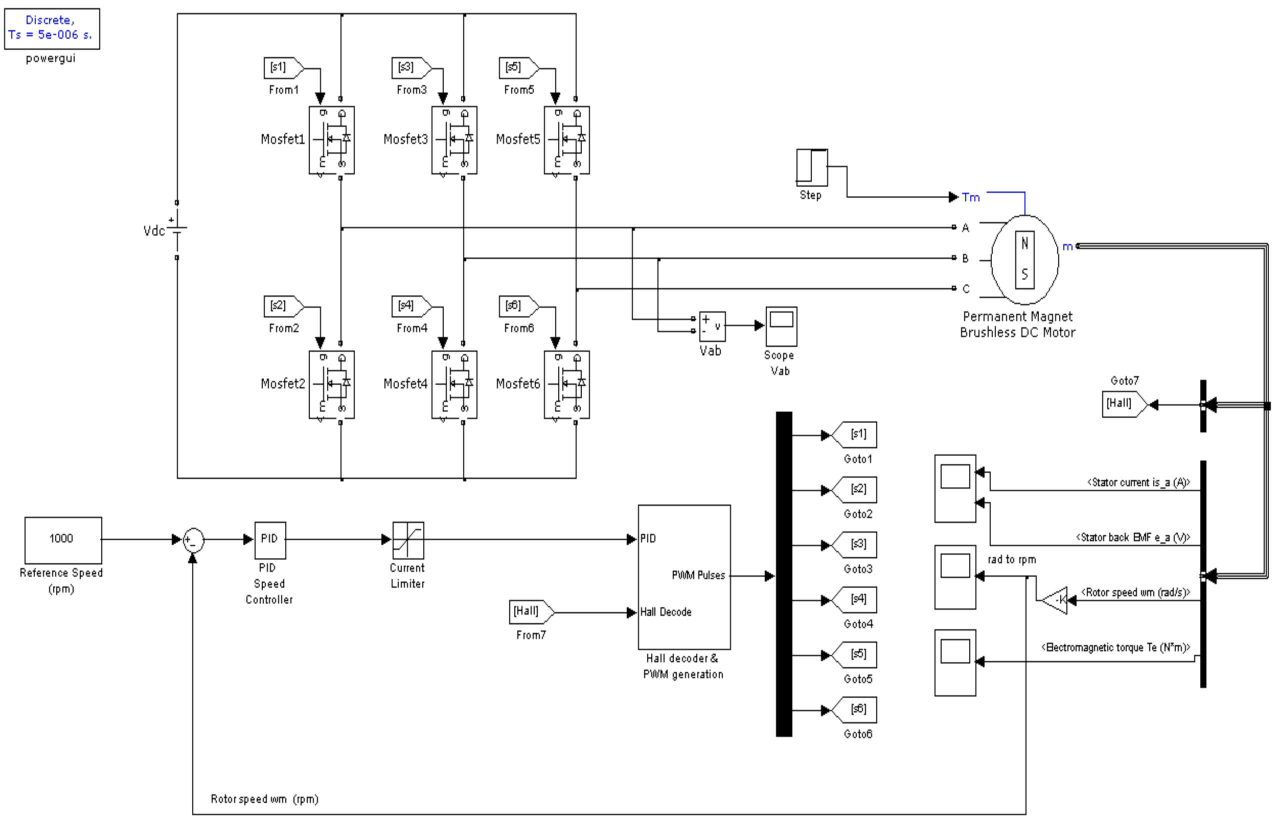


Fig. 6.Simulation Circuit for the speed control of BLDC motor drive system using PID controller.

CONCLUSION

In this paper, the PID controller was used as a vital technical tool for the closed loop speed control of BLDC motor drive system.The system controller design and the parameters identification are based on the simulation carried out on using SIMULINK/MATLAB.Also the “Trial and Error method” of PID controller tuning is presented and applied to brushless DC motor. This method is feasible due to the unique and simplified structure of the BLDC motor. The PID controller thus designed has been simulated and observed to have good performance. The maximum overshoot is found to be very less which is a good result. So a speed controller has been designed successfully for closed loop operation of the BLDC motor and the motor runs very closed to the reference speed.

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