PID Controller Based Closed Loop Speed Control of BLDC Motor

[1]*M Priya, PG Scholar, Dept of EEE, G Narayanamma Institute of Technology and Science, Hyderabad*
[2]*N Malla Reddy, Professor, Dept of EEE, G Narayanamma Institute of Technology and Science, Hyderabad*
(*morapriya1225264@gmail.com*[1] , *nomula.nomula@gmail.com*[2])

Abstract— **As it is known that BLDC motors are rapidly gaining popularity because of its advantageous features like high efficiency, electronic commutation, high-speed range, maintenance free, good dynamic performance, etc. In many applications to obtain the desired characteristics, the speed of the BLDC motor is kept under control. In spite of many speed controllers being available, a PID controller is widely used in many industrial applications due to its ease of control and simple structure. This paper deals with the PID controller based speed control of BLDC motor, where the input to the BLDC motor is varied by the inverter, the inverter gating signals are controlled by hall sensor communication and the PID tuned current controller. This work mainly focuses on the closed loop operation and the design of speed controller. The proposed concept of speed control is developed using MATLAB/SIMULINK and the hardware is implemented on this concept using a PIC16F877A microcontroller with programmed PID controller code.**

Keywords—*Three phase inverter, Brushless DC (BLDC) motor, Hall sensors, Proportional-Integral-Derivative (PID) controller, PIC microcontroller.*

I. INTRODUCTION

In recent days most of the applications uses BLDC motors for their huge advantages, as for control techniques in industrial applications to aircrafts and as propulsion systems in automobiles, etc. The main reasons for rapid increase in popularity of BLDC motor are, it has excellent acceleration characteristics, less or no maintenance, good weight to power ratio, less noise when compared to brushed DC motor[1]. This special features has led to have a wide research area for the development of speed controllers for BLDC motor.

In conventional DC motor the current through the coil on the stator produces the air gap flux, but in BLDC motor unlike conventional dc motor the permanent magnet produces required flux rather then the windings on the stator[2]. The permanent magnet synchronous motor with flat toped trapezoidal Back EMF shape is known as Brushless DC motor. Due to the simple control and wide range of speeds, DC motors are used in many industrial applications as an electric drives but it has its own problems because of the presence of brushes. By eliminating the brushes on the motor we call it as Brushless DC motor which has similar characteristics like DC motor. BLDC motor withstands the problems of electric erosion and mechanical friction.

Due to the absence of brushes in BLDC motor, they are commutated by electronic circuits. The stator coils are energised in a proper sequence in order to rotate the motor. To know which coil to be energize according to the sequence, for this we need to have knowledge on rotor position. Now a days BLDC motors are provided with inbuilt Hall sensors. Three hall sensors are available on the stator of BLDC motor for rotor position . These sensors are incorporated on the non-rotating part of the motor called stator. The details of pole passage near the position sensors is indicated[3] . Now the logic low and high signals are generated by the sensors according to the North pole and South pole of permanent magnet rotor movement. The appropriate sequence for commutation can be estimated based on these inbuilt Hall sensors and their communication signals in BLDC motor.

The aim is to result out controlled speed response of the BLDC motor by adopting PID controller. This paper work deals with the design of the Proportional Integral and Derivative controller for regulation of BLDC motor speed and to have a constant speed for varying set speeds or reference speeds. It is the closed loop speed control operation where the actual speed is compared with the set speed in order to generate the error, and this error is given to the PID controller. This not an instant problem solving method because here the actual speed and set speed are compared to process the error.

II. BLDC MOTOR

A. *Modelling equations of Brushless DC motor*

In BLDC motors the back EMF is trapezoidal indicating that mutual inductance between the rotor and stator is trapezoidal shape. The motor drive contains Brushless DC motor along with a three phase inverter. The motor commutation is done by making use of six power semiconductor devices for inverter which helps in energizing any of the two phases of the motor at a time, while setting the other phase as free [1]. The inverter switching algorithm is obtained by sensing the rotor position by Hall sensors, where the Hall sensors are placed 120^0 electrically on the stator of BLDC motor.

In the view of modelling the BLDC motor the following assumptions are made, considering per phase resistance for the stator windings is equal, constant self and mutual inductance, neglecting iron losses, inverter semiconductor devices are ideal.

The circuit equivalence of Brushless DC motor is shown in the Fig 1.

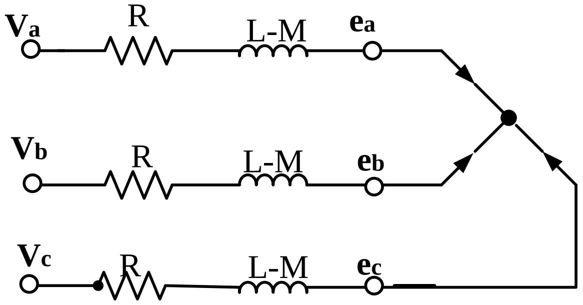

Fig 1. Equivalent electrical circuit model of BLDC motor

Mathematical equations in electrical and mechanical form of Brushless DC motor are:

$$V_a = Ri_a + (L-M)\frac{di_a}{dt} + e_a \qquad (1)$$

$$V_b = Ri_b + (L-M)\frac{di_b}{dt} + e_b \qquad (2)$$

$$V_c = Ri_c + (L-M)\frac{di_c}{dt} + e_c \qquad (3)$$

$$e_a = K_e\omega_m F(\theta_e) \qquad (4)$$

$$\mathrm{e_b = K_e\omega_m F(\theta_e - 2\pi/3)} \qquad (5)$$

$$e_c = K_e\omega_m F(\theta_e + 2\pi/3) \qquad (6)$$

$$T_a = K_t i_a F(\theta_e) \qquad (7)$$

$$T_b = K_t i_b F(\theta_e - 2\pi/3) \qquad (8)$$

$$T_c = K_t i_c F(\theta_e + 2\pi/3) \qquad (9)$$

$$T_e = T_a + T_b + T_c \qquad (10)$$

$$T_e - T_l = J\frac{d^2\theta_m}{dt^2} + \beta\frac{d\theta_m}{dt} \qquad (11)$$

$$\theta_e = p/2\,\theta_m \qquad (12)$$

$$\omega_m = \frac{d\theta_m}{dt} \qquad (13)$$

Where K= a, b, c
V_k= K^th phase voltage of BLDC motor
i_k= K^th phase current of BLDC motor
e_k= K^th phase back Emf
T_k= torque produced by the K^th phase
R= per phase resistance of BLDC motor
L= per phase inductance of BLDC motor
M= mutual inductance between phases
T_e= electromagnetic torque produced by motor
K_e= Emf constant
K_t= torque constant
ω_m= angular speed of rotor
θ_m= mechanical angle of rotor
θ_e= electrical angle of rotor

By rearranging equations (1), (2), (3), (7)

$$V_{ab} = R(i_a - i_b) + (L-M)\frac{d(i_a - i_b)}{dt} + e_{ab} \qquad (14)$$

$$V_{bc} = R(i_b - i_c) + (L-M)\frac{d(i_b - i_c)}{dt} + e_{bc} \qquad (15)$$

But, $i_a+i_b+i_c=0$ and neglecting mutual inductance Hence the above equations can be resolved as,

$$\frac{di_a}{dt} = -\frac{R}{L}i_a + \frac{2}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L}(V_{bc} - e_{bc}) \qquad (16)$$

$$\frac{di_b}{dt} = -\frac{R}{L}i_b - \frac{1}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L}(V_{bc} - e_{bc}) \qquad (17)$$

TABLE I BLDC MOTOR SPECIFICATIONS

BLDC Motor model	23F-2
Wattage	60W
DC Voltage	24V
Speed	1500RPM
Stator phase resistance	2.875Ohm
Stator phase inductance	8.5mH
Torque constant	1.4 N-M/A
Rotor inertia	$0.8*10^{-3}$Kg-m^2
Friction constant	$1*10^{-3}$

B. Speed control strategy of BLDC motor

The block diagram gives a brief understanding of Brushless DC motor speed control method using PID controller for obtaining the control signal.

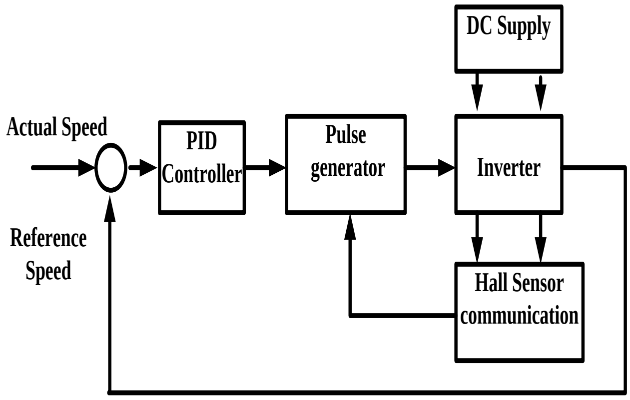

Fig 2. Speed control block diagram of BLDC motor

In above control process inverter has a lead role[2]. The inverter is used to feed the BLDC motor, which is being operated by a DC source. The rotor communication signals from the Hall sensors is given to the pulse generator. This paper uses Hall sensors position and it is decoded into Back EMF zero crossing points, The zero crossing points are passed through a logic circuit to generate high and low signals for the MOSFETS. Here the feedback signal is the actual speed which is compared with the reference speed to generate the error. This error is given to the PID control block the control signal from PID is given to the pulse generator[1]. The actual speed of BLDC motor and the position of permanent magnet rotor is measured by Hall sensors. When the rotor position sequence is generated then it is used for electronic commutation of the inverter.

III. CONTROLLER CIRCUIT

PID Controller design

In many industries, the control circuitry uses Proportional Integral and Derivative controllers because of easy tuning and requirement of less number of tuning parameters based on the application[3]. It is a simple parallel connection of P, I and D controllers with error signal as an input and the output is the control signal.

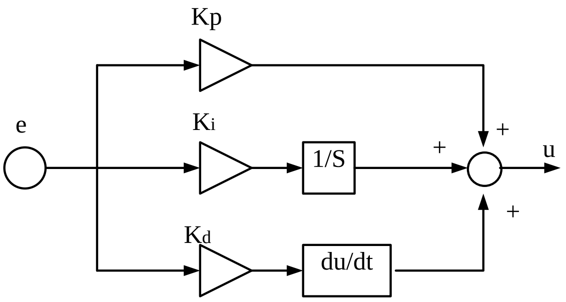

Fig.3 Model of PID controller

Proportional, Integral and Derivative controls which are the parameter characteristics are to be applied to the Fig. 3. The transfer function of the above controller is given as,

$$C(s) = K_p + \frac{K_i}{s} + K_D s \qquad (18)$$

$$C(s) = \frac{K_D S^2 + K_p s + K_i}{s} \qquad (19)$$

Where K_D= Derivative gain, K_i= integral gain, K_P= Proportional gain

The control function(u) from Fig.3 is the summation of Proportional gain times the error, Integral gain times the integral of error and the derivative gain times the derivate of the error[4]. The generated control signal is given to the plant and the plant responds according to the given control signal.

$$u = K_p e + K_i \int e\, dt + K_D \frac{de}{dt} \qquad (20)$$

Closed loop industrial process of about 95% contains PID controllers in control systems due to their excellent performance and simplicity if not optimal performance is required. The four major characteristics which are to be considered for closed loop operation are steady state error, settling time, rise time and overshoot.

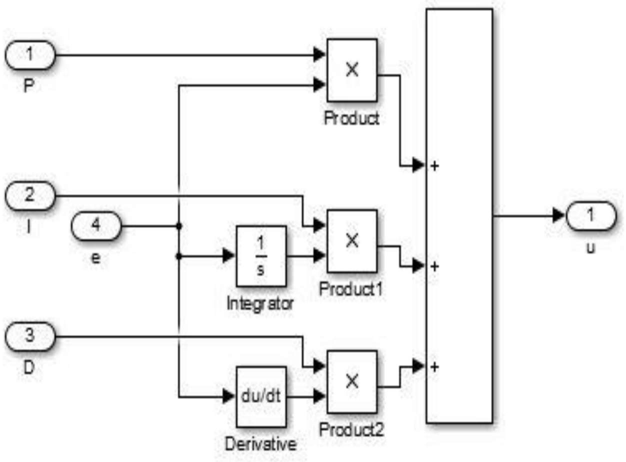

Fig. 4 Simulation model of PID controller

Steps for PID controller design

- Determine and improve the characteristics of the system
- For reducing the rise time use K_p.
- For eliminating the steady state error use K_i.
- For reducing the settling time and overshoot use K_D.

The transfer function of BLDC motor is given as,

$$G(s) = \frac{{}^{1}/_{K_e}}{\tau_e \tau_m s^2 + \tau_m s + 1} \qquad (10)$$

$$\tau_m = \frac{3JR}{K_e K_t} \qquad (11)$$

$$K_e = \frac{3 \times 2.875 \times 0.8 \times 10^{-3}}{1.4 \times 3 \times 10^{-3}} \qquad (12)$$

$$K_e = 1.64\ v - s/rad \qquad (13)$$

$$\tau_e = \frac{L}{3R} \qquad (14)$$

$$\tau_e = \frac{8.5 \times 10^{-3}}{3 \times 2.875} = 98.5 \times 10^{-5} sec \qquad (15)$$

$$G(s) = \frac{0.6097}{2.955 \times 10^{-6} s^2 + 0.003 s + 1}$$

τ_m = Mechanical time constant, τ_e = Electrical time constant
K_e = Back EMF constant, K_t = Torque constant

By calculation, the gains can be

K_p	K_i	K_d
2.35	666.7	0.0015

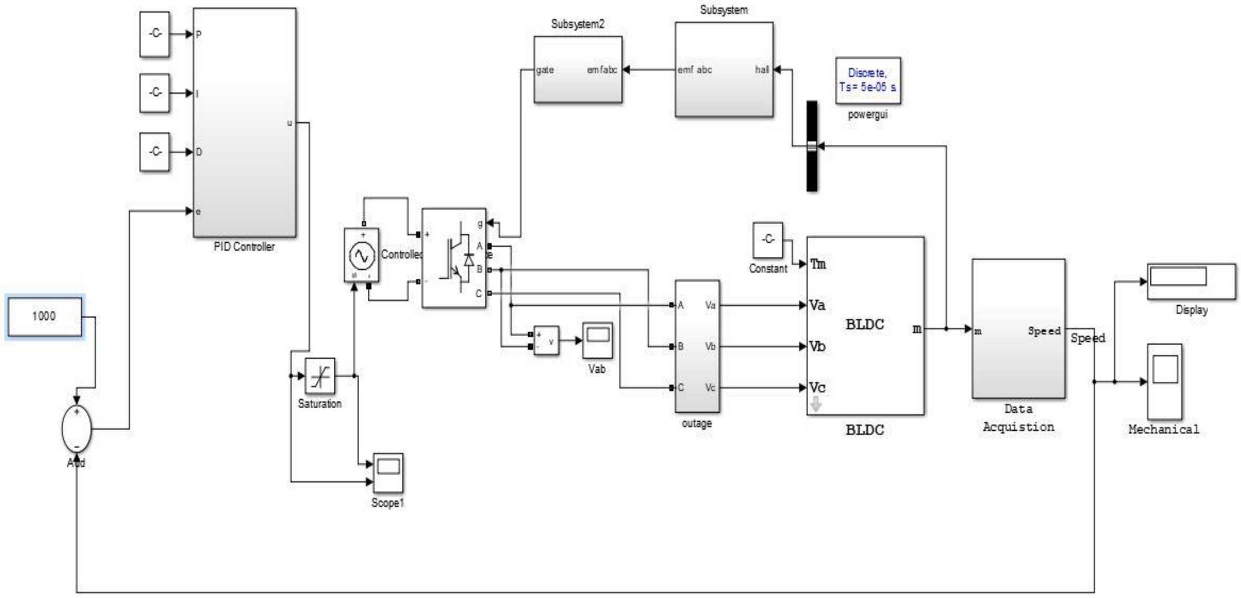

Fig. 5 Simulation model for speed control of Brushless DC motor

IV. DISCRIPTION OF HARDWARE

The simulation concept shown in the Fig. 5 is implemented using the PIC16F877A microcontroller. The Fig. 6 shows the hardware model for the speed control of BLDC motor using PIC16F877A microcontroller and the BLDC motor with inbuilt Hall sensors.

The PIC controller used in the hardware is of 40 pin Integrated circuit. Here the pulses are generated at 33rd – 38th pins of PORT B and given to the inverter switches through driver circuit Here the input voltage to the BLDC motor is varied by the inverter to obtain the desired set speed. The Hall sensors which are incorporated on BLDC motor give the analog signals to the microcontroller. The presence of analog to digital converter in the microcontroller, converters analog signal to digital signal. #

The program for closed loop speed control is written including with the values of PID gains, K_P, K_i, K_D to obtain the error by comparing the set reference speed and the actual speed of the motor for generating the switching pulses for the inverter. With the variation of the error in speed the available PID controller programme in the microcontroller will analyze the error and produces the appropriate gating signals to the inverter. The gating signals from the PIC microcontroller is given to inverter via driver circuitry. The diver circuit provides the Amplification of pulses and isolation for PIC microcontroller and MOSFET switches of the inverter from getting damaged.

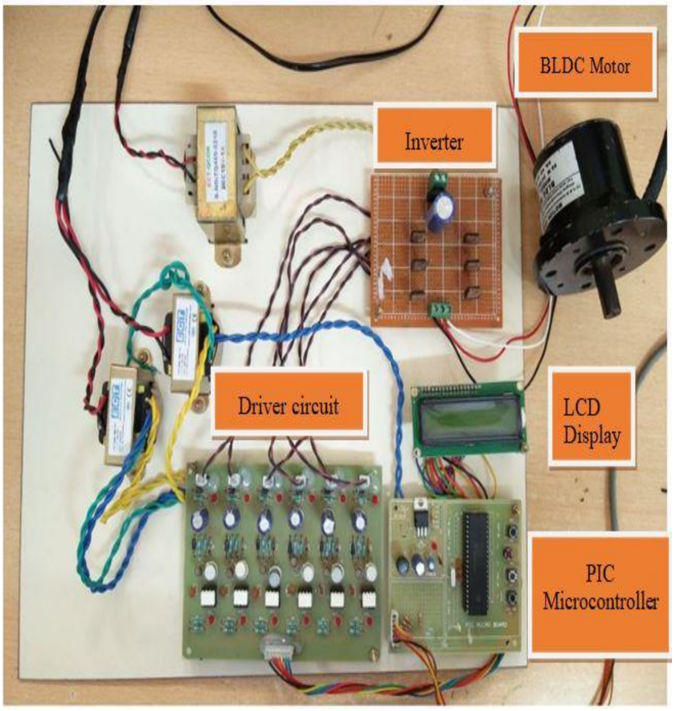

Fig. 6 Hardware model for closed loop speed control of BLDC motor using PIC16F877A microcontroller

V. MATLAB SIMULATION RESULTS

The simulation model for speed control of 24V, 60W BLDC motor Using PID control is carried out using MATLAB/SIMULINK software. The obtained speed control results are desirable for many industrial applications. In Fig. 7, Fig. 8 the actual speed of the motor is settling very near to the reference speed for 1000rpm and 1500rpm at No-load.

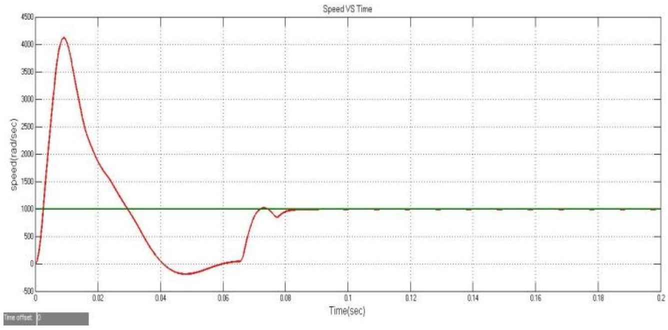

Fig. 7 Speed response of BLDC motor with PID controller with 1000rpm set speed

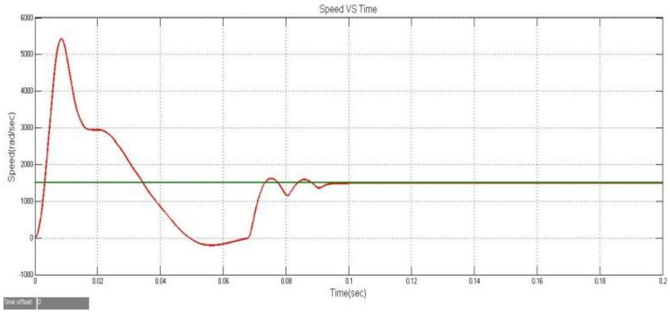

Fig. 8 Speed response of BLDC motor with PID controller with 1500rpm set speed

In Fig. 9 and Fig. 10 the speed of the motor is set to 1000rpm and 1500rpm respectively at 5N-m. The speed is settling near to the reference speed

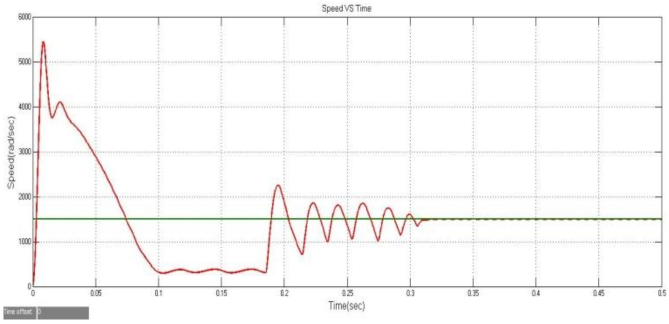

Fig. 9 Speed response of BLDC motor with PID controller with 1000rpm set speed

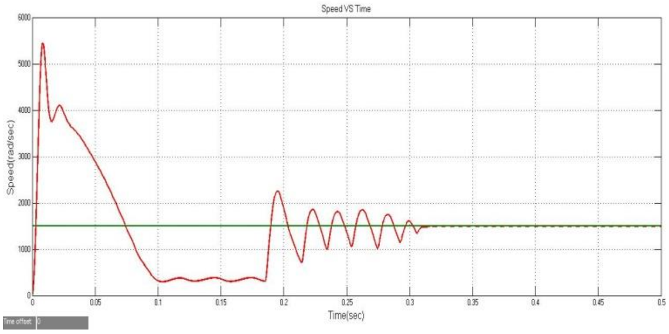

Fig. 10 Speed response of BLDC motor with PID controller with 1500rpm set speed

VI. HARDWARE RESULTS

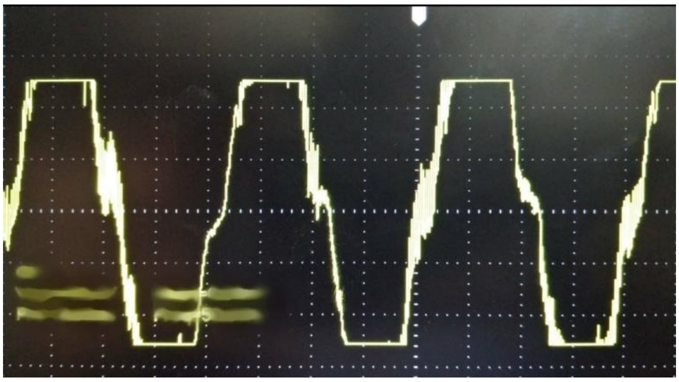

Fig. 11 Triggering pulses for 1000rpm

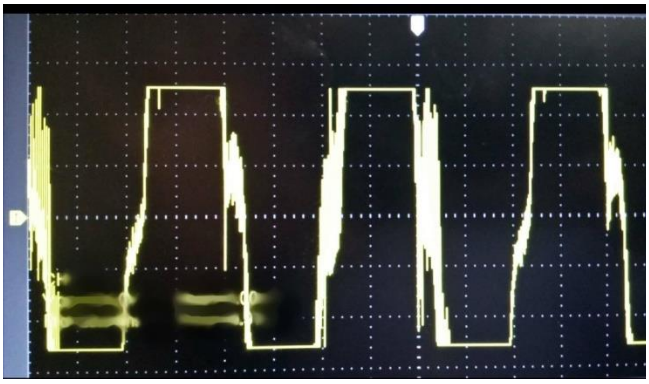

Fig. 12 Triggering pulses for 1500rpm

VII. CONCLUSION

In this paper, PID controller is used to obtain the desired speed under varying speed condition. The calculation of PID parameters and the design of control loop is carried out through MATLAB/SIMULINK model. From the simulation results, it is concluded that the speed response obtained by using PID controller is desirable and this speed control strategy is implemented in a hardware using PIC16F877A microcontroller with a programme for PID controller. Since the motor running speed is very near to the set speed due to the optimal PID controller design and hence closed loop speed control of BLDC motor is achieved.

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Author Profile:

M. Priya, PG student, Power Electronics and Electrical Drives, EEE Department, G Narayanamma Institute of Technology and Science. Areas of interest Power Electronics, Control systems, Electrical Drives.

Author Profile:

Dr. N. Malla Reddy, Professor, EEE Department, G Narayanamma Institute of Technology and Science. Areas of interest Power Electronics, Electrical Drives and Electrical Machines.