Implementation of Intelligent Controllers for Speed Control of BLDC Motor

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTSFOR
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OF

MASTER OF TECHNOLOGY

IN

POWER SYSTEM

SUBMITTED BY
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(2K21/PSY/06)

UNDER THE SUPERSVISION Of

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CANDIDATE'S DECLARATION

I, **Yashi Rani**, Roll No. **2K21/PSY/06**, M.Tech. (Power System), hereby declare that the project Dissertation titled "**Implementation of Intelligent Controllers for Speed Control of BLDC Motor**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is not imitated from any source without proper citation and is authentic. This work has not beforehand formed the root for the award of any Degree, Diploma, Fellowship, Associateship or any other similar title or acknowledgment.

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CERTIFICATE

I, hereby certify that the Project Dissertation titled "**Implementation of Intelligent Controllers for Speed Control of BLDC Motor**" which is submitted by Yashi Rani, Roll No. 2K21/PSY/06, Department of Electrical Engineering, Delhi Technological University,Delhi in partial fulfillment of the requirement for the award of the degree of Master ofTechnology is a testimony of the project work carried out by the student under our supervision. To the best of our awareness this work has not been submitted in part or full for any Degree or Diploma to this University or to a different place.

Place: **Delhi** **Prof. Uma Nangia**

Date: **(Supervisor)**

ABSTRACT

BLDC motor is a DC motor with concept of electronic commutation to provide better control over the speed characteristics of the motor compared to a mechanically commutated permanent magnet DC motor. This advantage comes at a cost of pulsating torque output from the motor, which makes the control strategy with speed reference more difficult as power will be pulsating if a constant voltage is set and under load there will be ripples in the actual motor speed.The control mechanism which uses feedback of the controlled parameter to calculate the error to a reference parameter and produces a control signal to minimize this error based on proportional and integral terms of the error signal by using any digital controller. Here we investigate a PID based control strategy v/s a PI control strategy using manual setting, auto-tuned and PSO algorithm. Application point of view we can use it in fully automatic machine, the behaviour of motor in that machines is continuously pulsating so the control factor comes into the role and we need the driver for it, the controlling part study with optimization that how truly we can enhance the result with our motor output. The study by simulating the BLDC motor on an industry standard software MATLAB Simulink. Due to their high efficiency, compact size, and precise control, Brushless DC (BLDC) motors are widely used in a variety of industrial applications. The traditional control methods for BLDC motors frequently face challenges in achieving optimal performance under varying operating conditions. Intelligent control techniques, such as fuzzy logic control (FLC) and neural network control (NNC), have shown promising results in this area.

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LIST OF ABBREVIATIONS

PSO	Particle Swarm Optimization
BLDC	Brushless DC
DC	Direct Current
PID	Proportional Integral Derivative
PI	Proportional Integral
FLC	Fuzzy Logic Control
NNC	Neural Network Control
RMS	Root Mean Square
BEMF	Back EMF
PMSM	Permanent Magnet Synchronous Motor
BDCM	Brushless DC Motor
EMF	Electromotive force
PWM	Pulse Width Modulation
BLDDCM	Brush Less Direct Drive Controlling Motor
FB	Feedback
TTL	Transistor Transistor Logic
SI	Swarm Intelligence
CC-VSI	Current Controlled Voltage Source Inverter
IGBT	Insulated Gate Bipolar Transistor
PMBLDCM	Permanent Magnet Brushless DC Motor
SP	Set Point
PV	Process Variable

LIST OF SYMBOLS

°	Degrees
ω_{ref}	Reference Speed
ω_m	Rotor Speed
T_{ref}	Reference Torque
τ	Torque
Ωm	Angular momentum
$\emptyset r$	Rotor Position Angle
R_s	Stator Resistance per Phase
L_s	Stator Inductance per Phase
M	Mutual Inductance per Phase
K_p	Proportional Constant
K_i	Integral Constant
K_d	Derivative Constant
q	Angular position of the rotor
Lm	Flux linkage
J	Moment of inertia
B	Damping constant
Te	Electromagnetic torque
Tl	Load torque
e(t)	Speed error
i_a, i_b, i_c	Motor phase currents
e_a, e_b, e_c	Motor phase back emfs
v_{as}, v_{bs}, v_{cs}	Stator phase voltages

CHAPTER 1

INTRODUCTION

1.1 BRUSH LESS DIRECT CURRENT MOTOR

The dynamic equivalent circuit is utilised to understand and evaluate the BLDC motor's transient behaviour [1]. The BLDC motor is more effective in nature for electric vehicles, and it has a relatively greater efficiency than other asynchronous motors. It also has a good, precise control [2]. Electrical controller activates a transistor or other solid-state switch to continually rotate the motor. A single phase as well as three phases can be used with the BLDC motor [3]. Hall effect sensors use current signals produced by the magnetic field, while hysteresis current controllers measure the error, give a result, and control on the basis of that [4]. For regulating purposes, the PI controller employs the actual measured speed and the reference speed [5]. The three parts of a PID controller work as follows: the integral part may minimise steady-state error; the proportional part can reduce the disturbances for system's error response; and the proportional part can improve the dynamic response with system stability [6]. The windup PI control and hysteresis current controller can reduce settling time and significant overshoot [7]. Hall effect sensor and hysteresis current controller are used to take position or displacement feedback and control the motor's speed. The motor will be quieter when there is less overshoot [9]. A controller can operate an electronic switch by receiving input data on the rotor position learned by detecting the hall effect [10]. The speed-position estimator technique is shown to be consistent under a variety of speeds and loads using the proposed single Hall approach, which is utilised to compare other strategies. The 160° approach also provides higher RMS phase voltage, smaller ripple for the produced torque and DC-link current, and overall superior BLDC motor performance when compared to the 120° and 150° procedures [11].

In order to decrease the voltage drop brought on by BEMF when running a BLDC motor at a high speed, the BEMF constant is made to be small. However, since the BEMF constant and the torque constant are the same, it results in a small initial torque and a long transient period. One of the disadvantages of a BLDC motor in high-speed applications [12]. It was found that ferrite magnets were a good substitute for magnetic rare-earth elements in terms of cost and manufacturing effectiveness. However, the residual magnetic flux density of the ferrite magnet is lower than that of the neodymium magnet. The ferrite permanent magnet cannot produce a significant amount of torque as a result. To solve this problem, ferrite permanent magnet motors were developed; their torque is on par with neodymium permanent magnet motors, which is why neodymium permanent magnet stacking is used in BLDC motors [13]. Due to the brush drop's neglect, brush-less DC motors are effective and adequate in terms of weight. They are also capable of regenerative braking [14].

1.2 COMPARISON WITH CONVENTIONAL MOTORS

In a typical DC motor, the armature coil windings and a set of electrical contacts on the rotor (referred to as the commutator) are connected via an electrical circuit created by the brushes. The stationary brushes come into contact with various parts of the revolving commutator as the armature spins on its axis. The armature coil closest to the stationary stator (permanent magnet) is always supplied with electrical current thanks to a series of switches made up of the commutator and brush system.

The permanent magnets of a BLDC motor revolve in place of the electromagnets, which are stationary in a conventional BLDC motor. By doing this, the issue of how to send current to a moving armature is solved. An assembly of commutator is swapped out with an electronic intelligent controller to do this. The controller uses a solid-state circuit rather than a commutator to carry out the same power distribution seen in a brushed DC-motor.

- Increased dynamic response
- Long lifespan;
- Low noise operation;
- Higher speed ranges;
- High efficiency

Compared to brushed DC-motors, BLDC motors require a more sophisticated electronic speed controller to operate. This is due to the brushless DC motor's need for a potentiometer or rheostat to control its speed, which is wasteful but acceptable for applications with a limited budget.

1.3 BRUSH LESS DIRECT CURRENT AND PERMANENT MAGNET SYNCHRONOUS MOTOR

According to a recent study, the induction motor may face substantial competition from permanent magnet motor drives, such as the permanent magnet synchronous motor (PMSM) and the brushless dc motor (BDCM), for servo applications. The BDCM requires rectangular stator currents and a trapezoidal back emf to maintain constant torque, but the PMSM requires sinusoidal back emf and sinusoidal stator currents to maintain constant torque.

Both in the commercial sector and the setting of academic research, there is some misunderstanding regarding which model should be used in particular circumstance. The only significant differences between the PMSM and the standard wound rotor synchronous machine are the absence of damper windings and the use of a permanent magnet rather than a field winding for excitation. Therefore, d, q models of the PMSM can be created by eliminating the equations for the damper windings and field current dynamics from well-known synchronous machine models.

The transformation of the synchronous machine equations from the abc phase variables to the d, q variables cause all sinusoidally fluctuating inductances in the abc frame to be compelled to become constant in the d, q frame. Transferring the equations to the d, q frame does not seem to be desired since inductances won't be constant after transformation. This is because inductances in the BDCM motor do not vary sinusoidally in the a, b, c frame because the back emf is not sinusoidal. As a result, it is recommended that BDCM use the ABC phase variables model. Furthermore, the way the BDCM is modelled makes it easy to analyse torque dynamics in great detail, which would not be possible with any simplifying assumptions.

1.4 ROLE OF CONTROLLER

In this study, the suggested intelligent controllers are created and used to precisely regulate the speed of a BLDC motor. The hardware design and fabrication of the BLDC motor drive, the creation of clever control algorithms, and the experimental verification of the implemented controllers make up the system's three phases.

The initial stage of hardware setup entails choosing and integrating the necessary parts for the BLDC motor drive, including power electronics, microcontrollers, and sensors. The motor driving circuitry is made to give the motor the required power and control signals. The sensors are used to gauge the motor speed and give the control system feedback. The BLDC motor drive system is used to implement and test the newly developed intelligent controllers.

To assess the performance of the controllers under various operating circumstances, such as load variations and speed references, experimental validation is carried out. To show the usefulness of the intelligent controllers in attaining precise speed control and enhancing the motor's dynamic responsiveness, the experimental findings are contrasted with those obtained using conventional control techniques.

1.5 INTELLIGENT CONTROLLERS

FLC and NNC are utilised to create the intelligent control algorithms. In order to approximate the non-linear relationship between the control inputs and outputs, fuzzy logic-based control uses language principles. Neural network-based control utilizes a trained neural network to approximate the control behavior. Both controller designs include establishing rule sets, choosing appropriate membership functions, and optimising the control parameters.

The conclusions of this research provide insights into the application of intelligent control approaches for BLDC motors speed control. The implemented controllers can be used to improve the effectiveness and BLDC motor drive systems performance in a various kind of industrial applications. The findings contribute to the improvement of intelligent control in the field of motor control systems.

1.6 PROBLEM STATEMENT

In the DC motors, loss occurs due to brushes, and we need them to change during maintenance due to its nature of friction on brushes by which they get damaged so we use Brush Less DC Motor and we can control its speed using electronic controller. But finding the right parameters for less settling time and less maximum overshoot is must. So rather using manual values and checking the result each time is not the optimum solution so for this we can use many metaheuristic techniques for optimising the values for controller. It makes possible to find different parameters if we want to vary the speed of the motor regularly in less time than finding them manually so I have used the Particle Swarm Optimization in it.

CHAPTER 2

BLDC MOTOR

2.1 PRINCIPLE OF BLDC MOTOR

An inverted dc motor with the armature and field situated on the stator and rotor, respectively, is a brushless dc motor. The brushless dc motor is similar to a permanent magnet ac motor in many ways, but it commutates the armature current electronically rather than using brushes. A BLDC motor is more durable than a dc motor by eliminating issues with the brush and commutator arrangement, such as sparking and commutator-brush wear out. Compared to a dc motor, it is significantly simpler to cool the armature windings because they are connected to the stator, which encourages heat transfer away from the windings.

A permanent magnet synchronous motor is transformed into a BLDC motor so that the back-emf is sinusoidal rather than trapezoidal. When the motor is being driven by a Current Source Inverter, it shouldn't be impossible to commutate a phase of the motor, but the "commutation region" of the back-emf should be as small as feasible. The flat constant section of the back-emf should be 120 degrees to provide torque consistently.

An optical position sensor can locate the rotor by measuring light using a phototransistor.

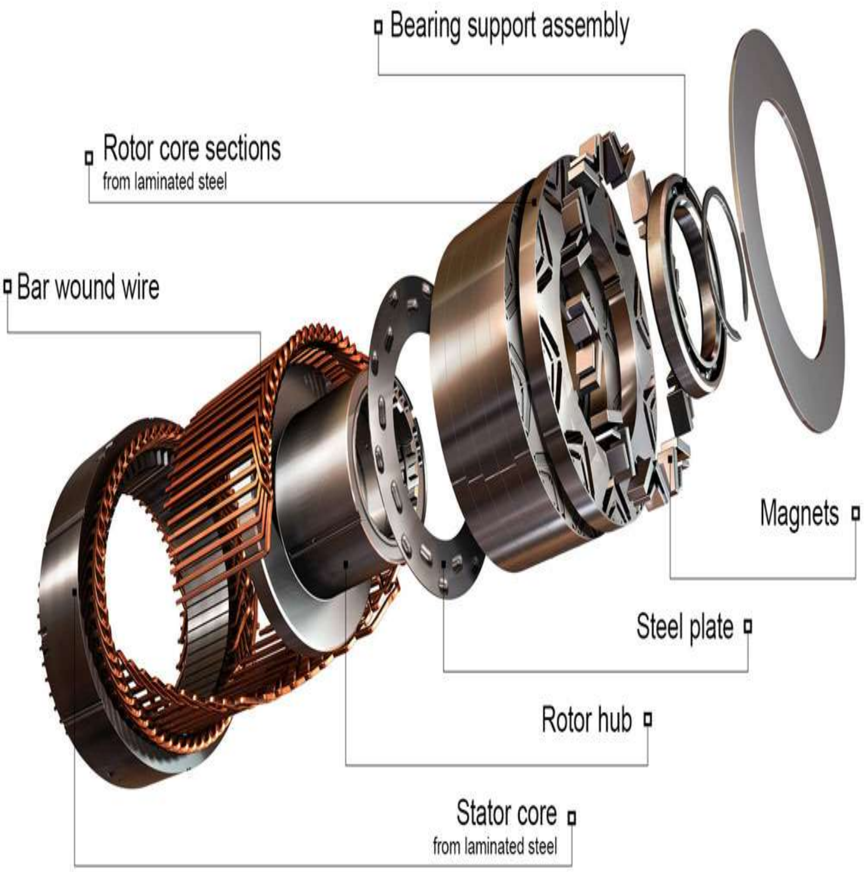

Figure No.2.1: Cross Sectional View of BLDC Motor [3]

2.1.1 Commutation

In order to generate a rotating magnetic field, the stator windings must be energised in a precise order. The stator windings are sequentially energised and deenergized during the commutation process to draw the rotor magnets and produce rotational motion. Usually, a control circuit that chooses the right time and order of the commutation is used to do this.

2.1.2 Magnetic Field Interaction

The permanent magnets in the rotor are affected by the magnetic field created as the stator windings become energised. By aligning with the magnetic field generated by the stator, the rotor can respond to a changing magnetic field. The interaction between the stator's and rotor's magnetic fields generates a torque that propels the motor's rotation.A rotor position sensor is necessary for a brushless DC motor in order to start and provide the correct commutation sequence for turning on the power devices in the inverter bridge. As a result, issues with brushes and commutator configurations, such as sparking and commutator brush wear, are avoided.

2.1.3 Electronic Commutator

A BLDC motor's commutation is accomplished by electronically altering the flow of current to the stator windings. Transistors and other solid-state switches, as well as power electronic components, are frequently used for this. A motor controller or drive, which keeps track of the rotor position using rotor position sensors, manages the switching of the current in synchrony with the rotor position.

2.1.4 Rotor Positioning Sensing

Rotor position sensors are frequently used in BLDC motors to precisely control the commutation and guarantee the proper energization of the stator windings. These sensors, which include Hall effect sensors, magnetic encoders, and optical encoders, give information on how the rotor magnets are positioned in relation to the stator windings. The motor controller uses this data to decide on the ideal timing for commutation.

2.1.5 Continuous Rotation

The BLDC motor may achieve continuous rotation by repeatedly repeating the commutation process and preserving the synchronised contact between the stator and rotor magnetic fields. The frequency and amplitude of the current applied to the stator windings can be changed to alter the rotation's speed and direction.

Voltage source-based drives and current source-based drives are the two primary categories of brushless dc motors. While current source-based drives utilise a current source to power the motor, voltage source-based drives use a voltage source. The pictures below illustrate the sinusoidal phase back emf of a BLDC motor in Fig. 2.3 and the trapezoidal waveforms of emfs for each phase in Fig. 2.2.

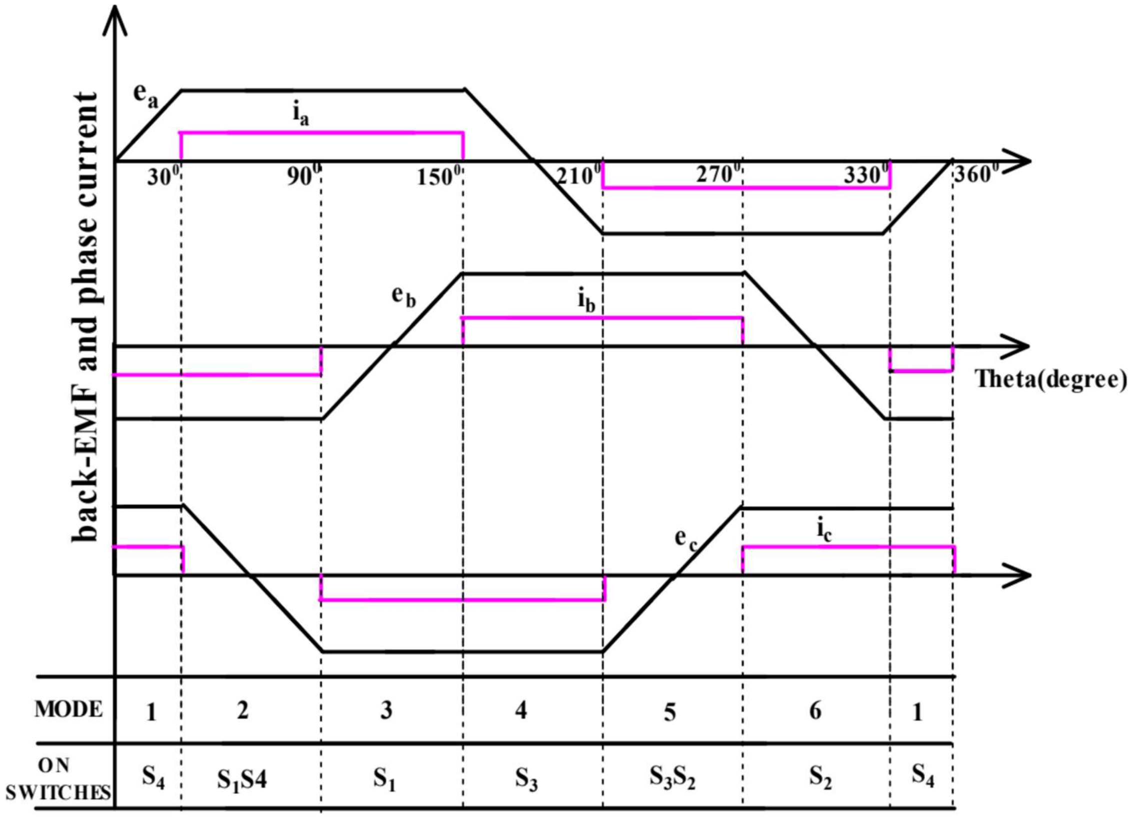

Figure No. 2.2: Trapezoidal Back EMF and Phase Current [4]

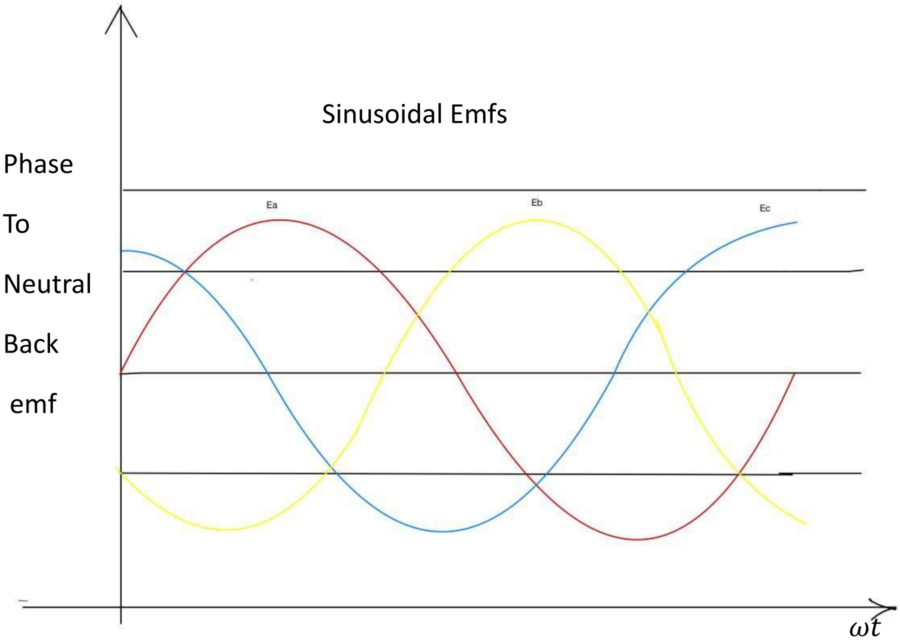

Figure No. 2.3: Sinusoidal Back emf (Phase to Neutral)

2.2 A BRIEF REVIEW ON CONTROL OF BLDC MOTOR

In a variety of applications, precise control of Brushless DC (BLDC) motors is essential for getting the best performance, efficiency, and control. In order to control the speed, position, and torque of BLDC motors, a variety of control approaches are frequently used. Here is a summary of several frequently employed control techniques:

2.2.1 Trapezoidal Control

A straightforward and popular control method for BLDC motors is trapezoidal control, commonly referred to as six-step commutation. The electrical cycle is split into six parts, each of which energises two phases simultaneously. The rotor position sensors, which are typically Hall effect sensors, determine the commutation sequence. For BLDC motors, trapezoidal control offers effective torque and speed control and is relatively simple to use.

2.2.2 Sensor-Less Control

Methods of sensor-less control seek to do away with the requirement for rotor position sensors, thereby lowering cost and complexity. Several methods are used, including sensor-less vector control, observer-based estimate, and back electromotive force (EMF) sensing. These techniques estimate the rotor position using data from the back EMF produced by the motor windings. Although sensor less control can save costs and increase dependability, it may not be suitable for all operating scenarios or low-speed operation.

2.2.3 Field-Oriented Control (FOC)

Field-Oriented Control (FOC) is a complex control method that permits accurate control of BLDC motors. FOC is often referred to as vector control. The motor currents are separated into two orthogonal components: a component that generates torque (known as the direct axis) and a component that magnetises (known as the quadrature axis). FOC can accomplish accurate control of torque, speed, and position by independently managing these components. Rotor position sensors or sensorless estimating algorithms can provide the precise knowledge of the rotor location that FOC requires.

2.2.4 Direct Torque Control (DTC)

Direct Torque Control (DTC) is a control technique that focuses on directly adjusting the motor's torque and flux without the requirement for an exact measurement of the rotor position. In order to determine the best switching states for the inverter, it makes use of look-up tables and hysteresis comparators. Excellent torque and flux control, rapid reaction, and great dynamic performance are all features of DTC. Nevertheless, compared to other control strategies, it might produce larger switching losses and high-frequency harmonics.

2.2.5 Model Predictive Control (MPC)

Model Predictive Control (MPC) is a sophisticated control technology that predicts the behaviour of the system in the future using a mathematical model of the motor to optimise control actions. To produce the best possible control signals, it takes system limits and desired performance objectives into account. MPC may need a lot of processing resources yet can offer outstanding performance and robustness.

The particular needs of the application, such as the speed range, torque control, cost, complexity, and dependability, determine the control mechanism to be used. Trapezoidal control or sensor-less approaches are advantageous for straightforward applications, while FOC, DTC, or MPC are necessary for demanding applications to achieve higher precision and dynamic performance.

Overall, considerable improvements in BLDC motor control have made it possible to control these motors accurately and efficiently in a variety of applications. The requirements and limitations of the particular application should be carefully considered before choosing the best control mechanism.

2.3 BLDC DRIVE OPERATION WITH PWM INVERTER

In essence, this is an electronic motor that needs a three-phase inverter at the front end, as depicted in Fig. 2.4. The inverter functions as an electrical commutator in self-control mode, receiving the switching logical pulse from the absolute position sensors. The motor is referred to as an electronic commutated motor as well.

Basically, the inverter can operate in the following two modes.

- $\frac{2\pi}{3}$ angle switch-on mode
- Voltage and current control PWM mode
- $\frac{2\pi}{3}$ Angle switch-on mode

The wave seen in Fig. 2. is used to operate the inverter in this mode. The inverter's six switches (T1 through T6) work together to position the input dc current Id in the middle of each phase voltage wave, symmetrical for a 2/3 angle. The angle represented is the current wave's advance angle with respect to the voltage wave when it is zero. Two switches, one in the upper group and the other in the lower group, are both on at any given time. When the supply voltage Vdc and current Id are applied across the line ab (phase A and phase B in series), for instance, so that Id is positive in phase a, T1 and T6 are on at instant t1.

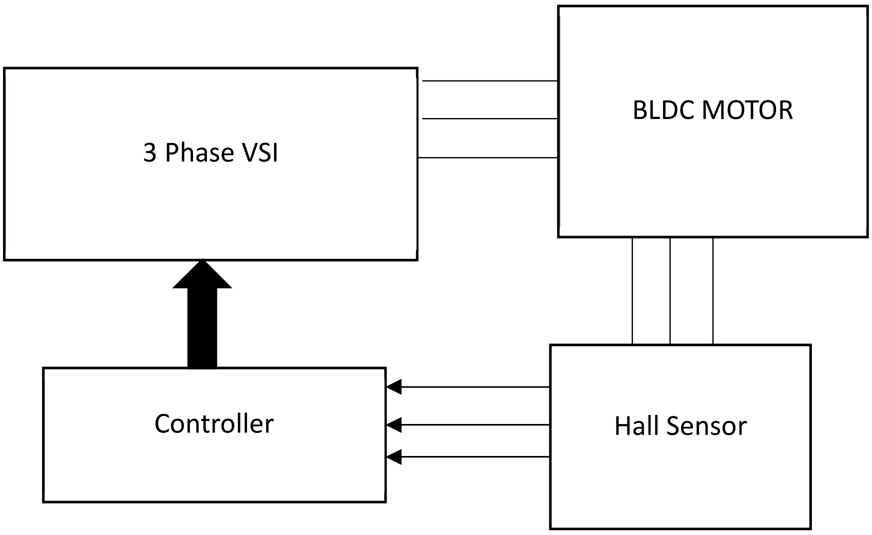

Figure No. 2.4: BLDC Motor Drive System

However, the phase B and /3 intervals (the centre of phase A) were negative. While T2 and T6 are turned on, T1 continues to conduct at the full 2/3 angle. In contrast to phase A carrying +Id, this switching commutates -Id from phase B to phase C. The conduction pattern changes every 2/3 angle indicator switching modes in a whole cycle. Devices must be switched on or off at the exact wave moments, according to the absolute position sensor. In essence, the inverter functions as an electrical commutator that is sensitive to rotor position. In contrast to phase A carrying +Id, this switching commutates -Id from phase B to phase C. The conduction pattern changes every 2/3 angle indicator switching modes in a whole cycle. Devices must be switched on or off at the exact wave moments, according to the absolute position sensor.

In addition to presenting the findings of experiments using the abc model to get to learn the BDCM behaviour of speed drive, this research examines the usage of the direct, quadrature model of the PMSM to explore transient PMSM servo drive behaviour of a high-performance vector controlled.

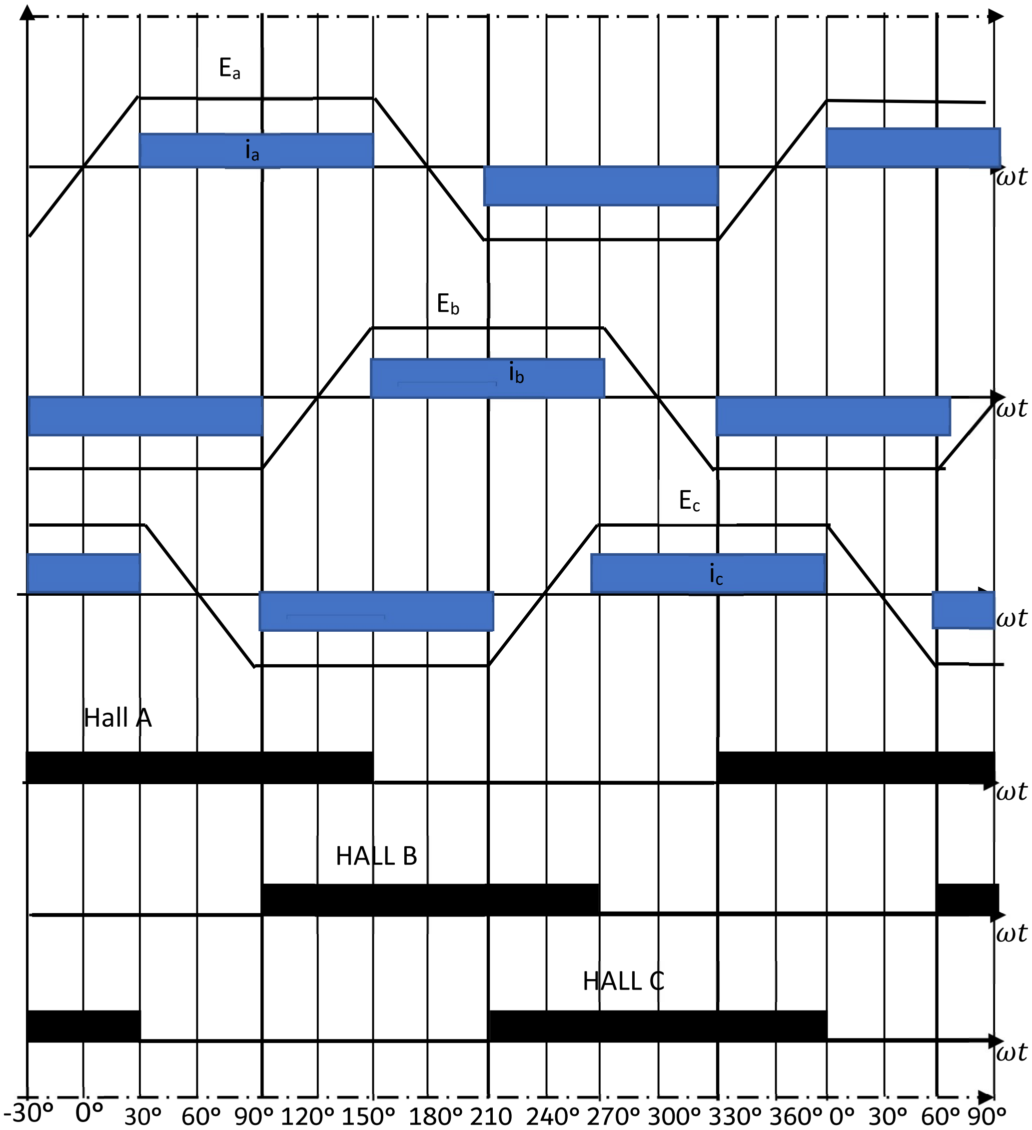

Figure no. 2.5: Switching of the Current and Back EMF of 3 Phase VSI

2.4 VOLTAGE AND CURRENT CONTROL PWM MODE

Only when the devices were successively ON, OFF for a 2/3 angle time were the inverter switches in the prior mode regulated to provide commutator function. For continuous control of voltage and current at the machine terminal-end, the switches can also be operated in PWM chopping mode. Current regulated functioning of the inverter and feedback (FB) mode are the two main chopping modes. In order to regulate the machine average current Iav and the machine average voltage Vav, devices are turned on and off according to a duty cycle in both of these modes.

2.5 DYNAMIC MODELLING

A collection of mathematical equations that describe the behaviour of a Brushless DC (BLDC) motor in response to applied voltage, current, and mechanical loads are derived during the dynamic modelling process. These models are necessary for building control algorithms that will produce the desired performance and for comprehending the motor's dynamic response. The voltage-based method and the flux-based approach are two different ways to model BLDC motors. Here, we'll concentrate on the widely applied voltage-based method.

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d\begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix}}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2.1}$$

where the stator phase voltages are vas, vbs, and vcs; The stator phase currents are ia, ib, and ic, while Rs is the stator resistance per phase. Phases a, b, and c's self-inductances are represented by the symbols Laa, Lbb, and Lcc; phase a, phase b, and phase c's mutual inductances are represented by the symbols Lab, Lbc, and phase c's electromotive forces by ea, eb, and ec. All of the windings' resistance has been considered to be equal.

$$L_{aa} = L_{bb} = L_{cc} = L \tag{2.2}$$

$$L_{aa} = L_{bb} = L_{cc} = LL_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \tag{2.3}$$

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix}}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2.4}$$

$$v_{as} = v_{ao} - v_{no}, v_{bs} = v_{bo} - v_{no} \; and \; v_{cs} = v_{co} - v_{no} \tag{2.5}$$

$$i_a + i_b + i_c = 0 \tag{2.6}$$

$$M_{ib} + M_{ic} = -M_{ia} \tag{2.7}$$

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2.8}$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \tag{2.9}$$

Where m is the angular rotor speed in radians per second, m is the flux linkage, r is the rotor position in radians, and fas, fbs, and fcs have the same shape as ea, eb, and ec with a maximum magnitude of 1. The trapezoidal form of the produced emfs prevents them from having sharp corners.

The flux density function is smooth with no sharp edges, and the flux linkages are continuous functions. The overall flux density curve is smoother as a result of fringes.

$$T_e = [e_a . i_a + e_b . i_b + e_c . i_c]\omega_m \ (Nm) \tag{2.10}$$

$$J = J_m + J_l \tag{2.11}$$

$$J \frac{d\omega_m}{dt} + B\omega_m = T_e - T_i \tag{2.12}$$

$$\frac{d\theta_r}{dt} = \frac{p}{2}\omega_m \tag{2.13}$$

The system will be out of balance if the potential at the neutral point is ignored because the damping coefficient is tiny and frequently disregarded. To prevent this, change equation (2.14) into equation (2.16), add, and get the results shown below. The system will be in balance if the potential at the neutral point is taken into account because the damping coefficient is tiny and frequently ignored. To prevent this, change equation (2.14) into equation (2.16), add, and get the results shown below.

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = R_s(i_a + i_b + i_c) + (L - M)(pi_a + pi_b + pi_c) + (e_a + e_b + e_c) \tag{2.14}$$

$$v_{ao} + v_{bo} + v_{co} - 3v_{np} = (e_a + e_b + e_c) \tag{2.15}$$

$$v_{no} = \frac{[[v_{ao}+v_{bo}+v_{co}]-(e_a+e_b+e_c)]}{3} \tag{2.16}$$

$$x = Ax + Bu + Ce \tag{2.17}$$

$$x = [i_a \quad i_b \quad i_c \quad \omega_m \quad \theta_r]^T \tag{2.18}$$

$$A = \begin{bmatrix} \frac{-R_s}{L-M} & 0 & 0 & \frac{-\lambda_m f_{as}(\theta_r)}{J} & 0 \\ 0 & \frac{-R_s}{L-M} & 0 & \frac{\lambda_m f_{bs}(\theta_r)}{J} & 0 \\ 0 & 0 & \frac{-R_s}{L-M} & \frac{\lambda_m f_{cs}(\theta_r)}{J} & 0 \\ \frac{\lambda_m f_{as}(\theta_r)}{J} & \frac{\lambda_m f_{bs}(\theta_r)}{J} & \frac{\lambda_m f_{cs}(\theta_r)}{J} & \frac{-B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \tag{2.19}$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 00 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} \tag{2.20}$$

$$C = \begin{bmatrix} \frac{-1}{L-M} & 0 & 0 \\ 0 & \frac{-1}{L-M} & 0 \\ 0 & 0 & \frac{-1}{L-M} \end{bmatrix} \tag{2.21}$$

$$u = [v_{as} \quad v_{bs} \quad v_{cs} \quad T_l]^T \tag{2.22}$$

$$e = [e_a \quad e_b \quad e_c] \tag{2.23}$$

2.6 TYPICAL BLDC MOTOR APPLICATIONS:

Electronic motor drivers are expected to become very popular in the next five years, as consumers demand lower energy costs, better performance, reduced acoustic noise, and more convenient features.

2.6.1 Applications with Constant Loads

In these kinds of applications, the motor's speed variability is more significant than its speed precision. The load is directly linked to the motor shaft in applications with constant load. Fans, pumps, and blowers are a few examples of this category of application. These applications call for open loop, low-cost controllers.

2.6.2 Applications with Varying Loads

Brushless DC (BLDC) motors are frequently employed in numerous applications with a range of loads. BLDC motors are excellent for a variety of industries since they can withstand a variety of load circumstances. The following uses for BLDC motors involve variable loads like robotics, industrial applications, electric vehicles, HVAC system and home appliances.

2.6.3 Positioning Applications

Machines that utilise power transmission, such as gears or timing belts, fall under this category of industrial use. These machines' dynamic reaction is crucial, and they might frequently reverse their rotational direction. The three phases of a normal cycle are accelerating, constant speed, and deceleration and positioning. Throughout each of these stages, the machine's load could change, making the controller complex. Typically, these systems run in closed loops.

This class of industrial use includes devices that use power transmission, such as gears or timing belts. Dynamic responses from these machines are essential, and they frequently change the direction of their rotation. A typical cycle has three phases: acceleration, steady speed, deceleration and positioning. The machine's load could fluctuate during each of these phases, making the controller complex. These systems often operate in closed loops.

CHAPTER 3

PSO ALGORITHM

A metaheuristic optimisation technique namely Particle Swarm Optimisation (PSO) is motivated by the group behaviour of swarms. Due to its simplicity, efficiency, and efficacy in solving a variety of optimisation problems, it has attracted considerable attention. The PSO method is thoroughly described in this paper, together with its underlying concepts, operational procedures, mathematical formulation, and practical applications. Additionally, we investigate numerous PSO algorithm variations and extensions, highlighting their distinct advantages. Finally, we discuss the PSO research's advantages, disadvantages, and potential future directions.

Swarm Intelligence (SI) is an area of research that draws its inspiration from the group behaviour of social and natural swarms. It investigates how a bunch of simple, individual agents with limited knowledge might act intelligently. In-depth discussion of swarm intelligence's foundations, distinguishing traits, and practical applications are provided in this work. We look at the communication, collaboration, and self-organization processes that underlie swarm intelligence. Additionally, we present well-known swarm intelligence-inspired algorithms including ant colony optimisation, particle swarm optimisation, and bee algorithms.

To resolve optimisation issues, it imitates the group dynamics of a flock of birds. The balance between exploration and exploitation is one of the crucial factors in the success of the PSO. This precise balance enables the algorithm to navigate towards promising regions while avoiding premature convergence, effectively searching the solution space. In this part, we explore the meaning of the terms "exploration" and "exploitation" in PSO as well as the methods used to strike an optimal balance.

3.1 EXPLORATION

Exploration is the practise of exploring the solution space for uncharted areas that might hold more effective solutions. Particles in the swarm want to broaden their search area and cover a large portion of the solution space during the exploration phase. This is especially crucial early in the algorithm's development when the swarm's understanding of the problem domain is limited. Exploration assists PSO in avoiding local maxima and speeds up the search for globally optimal or nearly optimal solutions.

By encouraging particles to explore new territory, adding randomness to their movement promotes exploration. The introduction of random components into the algorithm equations is another method of incorporating randomness. Other methods include randomising the initialization of particles, perturbing updates to velocity and location, and initialising particles randomly.

The best solution so far discovered by any particle in the swarm is represented by the global best position, sometimes referred to as the global best solution or global best fitness value. Particles can be directed towards areas of the solution space that have shown promise by exchanging and using this information. However, for effective investigation, the influence of the best information available globally alone may not be enough.

3.2 EXPLOITATION

In order to take advantage of potential areas of the solution space, one must first utilise the knowledge that is currently available. It concentrates on stepping up the hunt for already well-known answers and further perfecting them. When the swarm has accumulated useful data on the issue landscape and is getting near to convergence in the algorithm's later stages, exploitation is essential.

The local best position or personal best is the best solution that each particle maintains for itself. Particles often take advantage of the area around their most well-known answer by using their personal best information. To improve fitness values, this aids in fine-tuning and refining the solutions.

PSO includes social interaction amongst particles that enables them to communicate and have an impact on one another's behaviour. Through this social interaction, promising solutions can spread across the swarm, encouraging the exploitation of areas with effective solutions and driving convergence.

Several ways have been put forth to strike the ideal balance between exploration and exploitation in PSO.

Controlling the trade-off between exploration and exploitation is the inertia weight parameter. Exploration is encouraged by a high inertia weight value since particles are more likely to sustain their momentum and explore a larger solution space. A low inertia weight value, on the other hand, favours exploitation since particles concentrate more on using the data from their individual and collective bests. The choice of neighbourhood topology affects how exploration and exploitation are balanced. Particle interactions and information sharing are impacted by many topologies, including global, ring, and random.

Effective exploitation is facilitated by a well-designed neighbourhood structure, which also supports exploration by varying the search process and allowing particles to converge towards optimal solutions. To strike a balance between exploration and exploitation, the algorithm's parameters can be changed dynamically while the optimisation process is running. According to the algorithm's development and the swarm's behaviour, adaptive strategies modify variables like the inertia weight, acceleration coefficients, and neighbourhood size.

The Particle Swarm Optimisation technique relies on both exploration and exploitation. It's critical to strike the correct balance between these two factors if you want to solve optimisation difficulties as effectively as possible. The PSO method can refine and enhance the existing solutions through exploitation while effectively exploring new parts of the solution space. PSO can strike the proper balance and efficiently navigate the search space by using tactics like randomization, the best available knowledge globally, the best available information locally, and social interaction. The exploration and exploitation techniques of PSO are being enhanced through ongoing research and testing, which will improve performance and enable it to handle increasingly challenging optimisation tasks.

3.3 FLOWCHART

PSO is a population-based optimisation algorithm that draws its inspiration from the social behaviour of fish schools and bird flocks. It is frequently employed to address optimisation issues.

Initialization: To begin, the algorithm initialises a population of particles in the search space at random. A particle's position and velocity are both known.

Evaluation: Using the objective function of the optimisation problem, the fitness of each particle in its current position is assessed.

Update Best Positions: If the current position has a higher fitness than the prior best, each particle updates its best position and fitness value.

Update Global Best: The best positions of all particles in the population are taken into account when updating the global best position and fitness value.

Velocity Update: Based on the particle's current velocity, the distance between its best position and current position, and the distance between the global best position and current position, the velocity of each particle is updated.

The effects of the particle's current velocity, personal best, and global best are each controlled by the parameters w, c1, and c2, respectively. A random number between 0 and 1 is produced using the rand() function.

Position Update: By adding each particle's velocity to its present position, the particle's position is updated.

Termination Condition: The algorithm repeats the aforementioned stages up to the point at which the termination condition is satisfied, which could be a set number of iterations or a successful conclusion.

$$V_i^{t+1} = W*V_i^t + C_1\ U_1^t\,(P_{b1}^t - P_i^t) + C_{2.}U_2^t\,(g_b^t - P_i^t) \tag{3.1}$$

$$P_i^{t+1} = P_i^t + V_i \tag{3.2}$$

V_i: velocity of the ith particle

P_{bi}: Personal best of the ith particle

P_i: Position of the ith particle

g_b: Global best

U_1 & U_2: Random numbers

C_1 & C_2: Acceleration Coefficients

W: Inertia Weight

Output: The method offers the optimal solution to the problem, which is the overall optimum location. Flowchart is given below as Figure 3.1

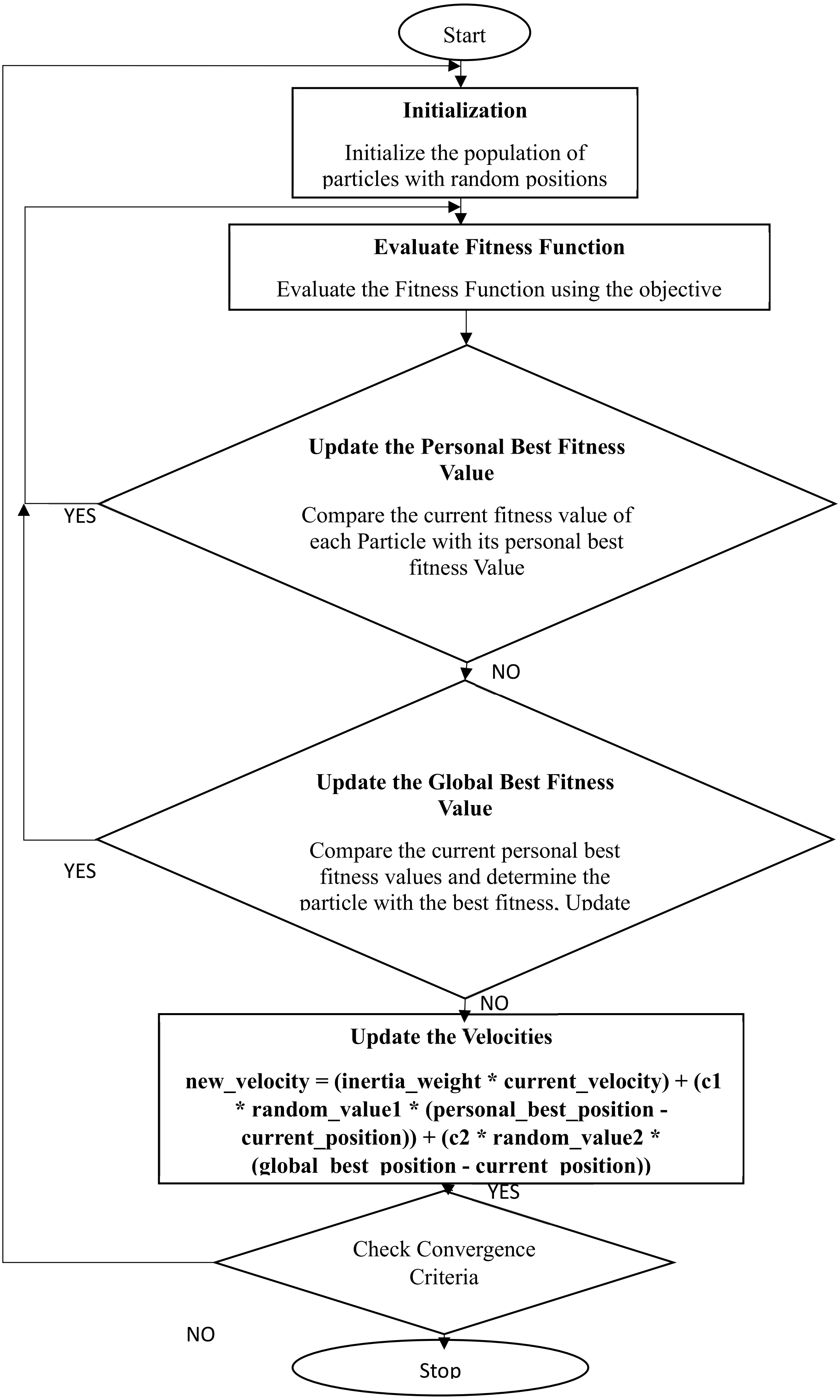
Start
Initialization
Initialize the population of particles with random positions
Evaluate Fitness Function
Evaluate the Fitness Function using the objective
Update the Personal Best Fitness Value
Compare the current fitness value of each Particle with its personal best fitness Value
YES
NO
Update the Global Best Fitness Value
Compare the current personal best fitness values and determine the particle with the best fitness. Update
YES
NO
Update the Velocities
new_velocity = (inertia_weight * current_velocity) + (c1 * random_value1 * (personal_best_position - current_position)) + (c2 * random_value2 * (global_best_position - current_position))
YES
Check Convergence Criteria
NO
Stop

Figure No. 3.1 Flowchart of PSO Algorithm

CHAPTER 4

DESIGN OF CONTROLLERS

4.1 PI CONTROLLER

In industrial control systems, a proportional integral derivative is a feedback mechanism used to account for discrepancies between a measured process variable and the desired set point.

The proportional and integral modes are computed by the PI controller. The impact of present error is determined by the proportional mode, while its recent error impact is determined by the mode of integral. Corrective action is decided upon based on the weighted sum of these modes. Because they are effortless to utilise and manageable to develop, PI controllers are frequently utilised in industry.

A feedback mechanism utilised in an industrial control system is a controlling of proportional integral derivative. A controller of PI in an industrial process makes an effort to reduce the discrepancy between a measured process variable and the desired set point by computing and then generating the necessary corrective action.

$$output(t) = K_P . e(t) + K_I e(\tau) d\tau \tag{4.1}$$

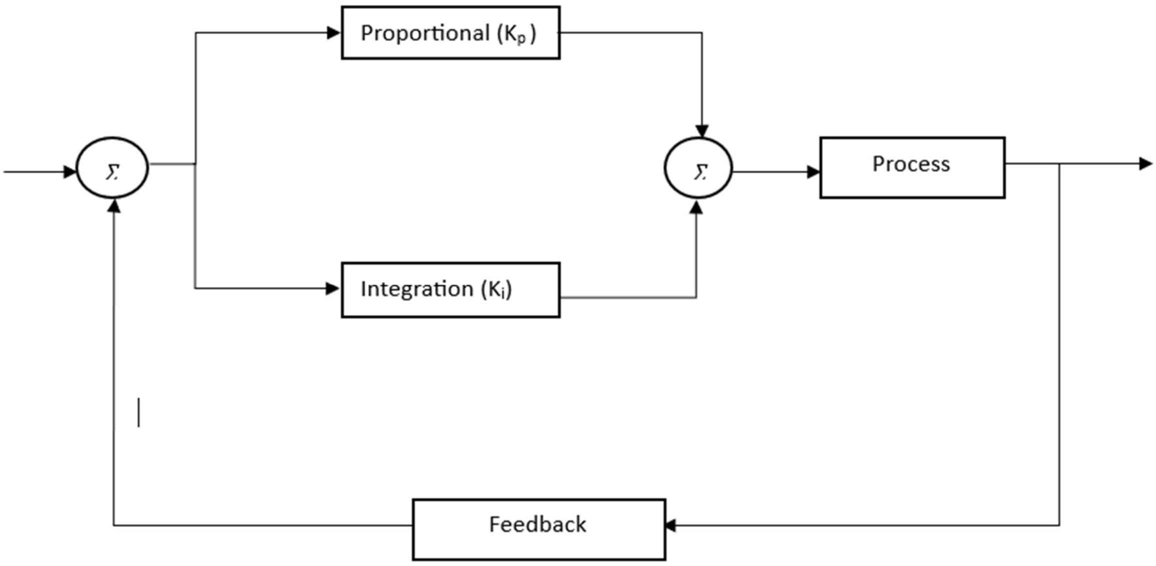

Figure No. 4.1: Block Diagram of PI Controller

where e(t) = set reference value – actual calculated

In order to manage the speed of Brushless DC (BLDC) motors, PI (Proportional-Integral) speed control is frequently utilised. It is a feedback control method that modifies the motor's input voltage or current in response to the discrepancy between the setpoint for the desired speed and the speed actually observed. The PI speed control algorithm for a BLDC motor is described as follows:

4.1.1 Speed Measurement

The BLDC motor's real speed is measured as the first stage in the PI speed control process. Several techniques, such as encoders, tachometers, or Hall effect sensors, can be used to do this. To determine the speed error, the recorded speed is compared to the desired speed setpoint.

4.1.2 Proportional Control

Control signals that are proportional to the speed error are produced by the proportional component of the PI controller, which performs proportional control. The strength of the proportional reaction is determined by the proportional gain (Kp). The proportional control's output is determined by:

$$P = Kp * e(t) \tag{4.2}$$

4.1.3 Integral Control

The integral part of the PI controller helps to eliminate steady-state speed error by integrating the speed error across time. The error is accumulated, and a control signal is generated depending on the integral of the error. The magnitude of the integral response is determined by the integral gain (Ki). The integral control's output is determined by the formula:

$$I = Ki * \int e(t)\, dt \tag{4.3}$$

$$e(t) = \omega_{ref} + \omega_m(t) \tag{4.4}$$

$\omega_m(t)$ is compared with the reference speed ω_{ref} and the resulting error is estimated at the n^{th} sampling instant as.

$$T_{ref} = T_{ref}(t-1) + K_P[e(t) - e(t-1)] + K_I e(t) \tag{4.5}$$

Where, KP and, KI are the gains of PI speed controller.

4.1.4 Control Signal Application

A Control Signal is used to modify the input voltage or current of a motor. This is done in BLDC motors by modulating the pulse width modulation (PWM) signal that powers the power electronic switches (such MOSFETs or IGBTs) in the motor. The average voltage or current applied to the motor windings is controlled by the PWM signal, which also regulates the motor speed.

4.1.5 Feedback Loop

During the control process, the motor speed is continuously measured, the control signal is calculated, and the motor input is modified. To respond quickly to speed changes and other disturbances, this loop is often run at a high frequency.

This controller’s output is regarded as the reference torque. Depending on the permitted maximum winding currents, a restriction is placed on the speed controller output. Using a constrained peak current magnitude, this controller generates the three phase reference currents (ia, ib, and ic). In accordance with the maximum permitted winding currents, this enables the controller to set a restriction on the speed of the windings.

4.1.6 Tuning

The effective tuning of the proportional and integral gains (Kp and Ki) determines the PI speed controller’s performance. To accomplish desired system behaviour, such as stability, response time, and disturbance rejection, tuning entails changing these benefits. It is possible to choose appropriate gain settings using a variety of techniques, including manual tuning or automated tuning algorithms.

The PI speed control algorithm can control a BLDC motor's speed and keep it close to the target setpoint by continuously modifying the control signal based on the speed error. While the proportional component offers a quick initial response to speed changes, the integral component helps avoid steady-state speed problems. These elements work together to provide a speed control of the system that is accurate and stable.

The reference currents create a constant unidirectional torque in phase with the corresponding BEMF and take the form of a quasi-square wave. The PWM current controller controls the three winding currents (ia, ib, and ic) within a narrow band. In order to operate the inverter devices, switching commands are created after the reference ia, ib, and ic motor currents are compared to the reference currents.

4.2 PID CONTROLLER:

An effective control technique known as a PID (Proportional-Integral-Derivative) controller constantly modifies an actuator in response to the error between the desired setpoint and the measured process variable. Its goal is to control the output of a system. It is a feedback control system that figures out how to keep diverse industrial processes stable, accurate, and responsive while also applying remedial actions.

4.2.1 Proportional Control (P)

The proportional part of the controller produces a result that is inversely proportional to the present discrepancy between the setpoint and the process variable. The error is multiplied by a proportional gain (Kp) to determine the output. The proportional control offers a quick response to system changes and helps lower the steady-state error.

4.2.2 Integral Control (I)

Based on the integral of the error, the integral component integrates the cumulative error over time and produces an output. This element addresses system biases and aids in the elimination of steady-state error. By combining the integral gain (Ki) and integral of the error, one may determine the integral control. It steadily reduces any residual error by continuously adjusting the output based on historical error data.

4.2.3 Derivatives Control (D)

The derivative component determines the error's rate of change and produces an output proportionate to that rate. The system reaction is dampened, which makes it less likely to overshoot or oscillate. The derivative gain (Kd) and derivative of the mistake are multiplied to determine the derivative control. By predicting the error's likely future trend and modifying the output accordingly, it aids in enhancing the system's transient response.

$$u(t) = \mathrm{Kp}\, e(t) + \mathrm{Ki}\int \mathrm{e}(\tau)d\tau + \mathrm{Kd}\, de(t)/dt \tag{4.6}$$

Where k_p , k_i , k_d are the proportional, integral, derivative coefficient of the PID controller respectively.

$$u(t) = Kp\{\, e(t) + \frac{1}{Ti}\int e(\tau)d(\tau) + Td\,\frac{de(t)}{dt}\} \tag{4.7}$$

In the standard form, we write the equation like above. Where we represent the T_i as K_p/K_i and T_d as K_d/K_p.

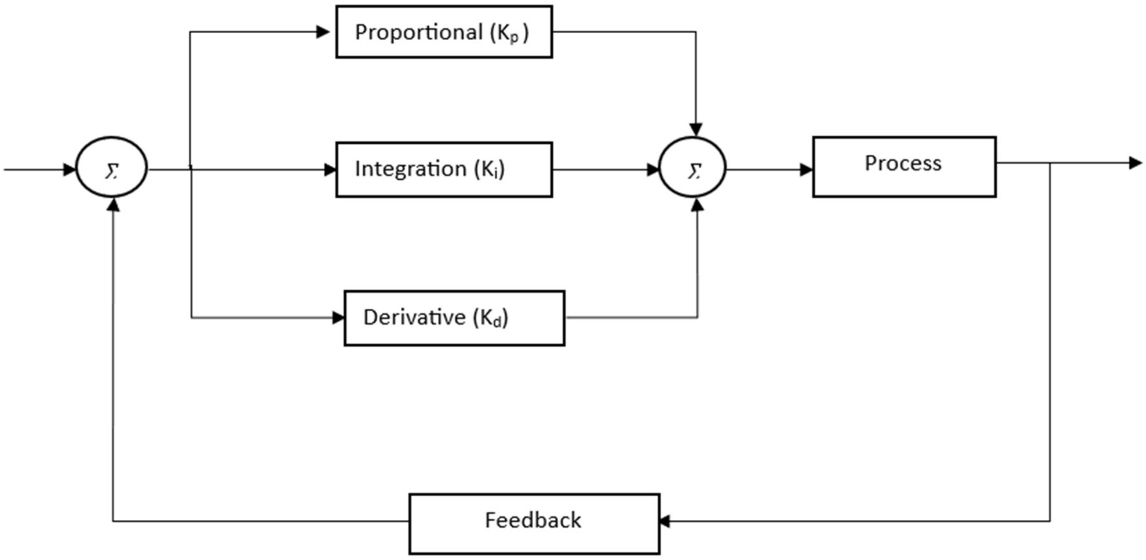

Figure Number 4.2: Block Diagram of PID Controller

4.2.4 Drawbacks of PID Controller

- Tuning Complexity: Careful tuning of the PID gains, which can be a difficult and repeated process, may be necessary to achieve optimal performance.
- Nonlinear Systems: Highly nonlinear systems or processes with considerable time delays may be difficult for PID controllers to handle.
- Sensitivity to Model Changes: PID controllers depend on a precise representation of the system, and changes in the dynamics of the system can have an impact on how well they work.
- Advanced control methods, such as model-based control or adaptive control algorithms, are sometimes used with PID controllers to alleviate some of these limitations.

CHAPTER 5

MODELLING OF BLDC MOTOR DRIVE SYSTEM

The drive system under consideration comprises of a PMBLDC motor, a universal bridge acting as an inverter, a PI and PID speed controller, a reference current generator, a current controller, a direct current source voltage, and a voltage DC source. These elements are all modelled and integrated for simulation under real-world circumstances.

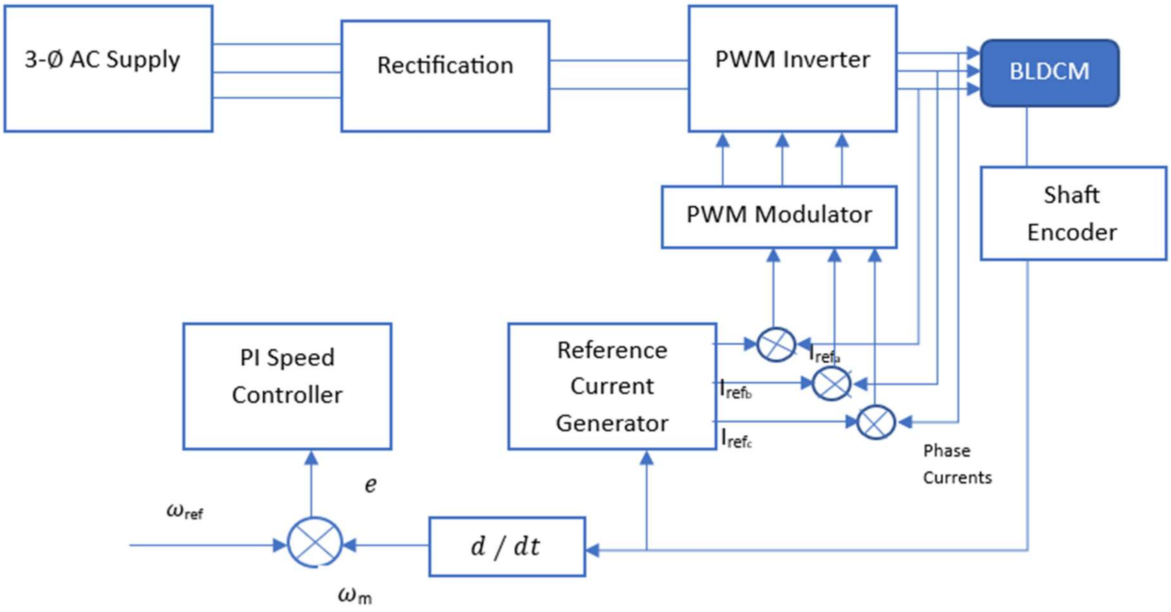

Figure no. 5.1: Block Diagram of BLDC Motor Controller Drive System Using PI Controller

The controlling of BLDC motor is done by using speed controller, it takes signal from hall sensor which provides signal based on measuring magnetic field by means of hall effect sensor. And current generator or voltage generator provides the signal back to the motor using feedback from it

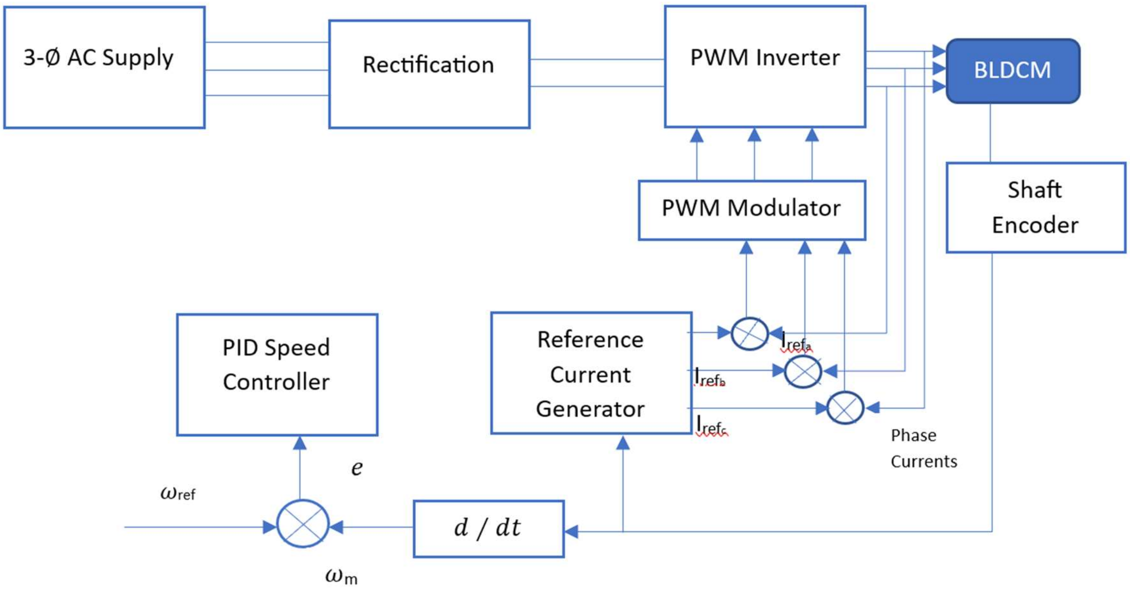

Figure no. 5.2: Block Diagram of BLDC Motor Controller Drive System Using PID Controller

5.1 ROTOR POSITION SENSORS

An essential component used in Brushless DC (BLDC) motors to track the position of the rotor while it is running is a rotor position sensor. It gives the motor control system the necessary feedback, allowing for precise phase commutation and facilitating smooth and effective motor operation.

The precise commutation and control of BLDC motors depend on a rotor position sensor. These sensors, whether they are Hall effect sensors, magnetic encoders, optical encoders, or resolvers, offer the essential feedback to calculate the rotor position and allow the motor to run effectively and precisely. BLDC motors typically have permanent magnets on the rotor and three-phase windings on the stator. Knowing the exact location of the rotor at any given time is essential for managing the commutation of the motor current phases by 120°. Using this knowledge, the right motor phases are energised to produce the required torque and rotational direction.

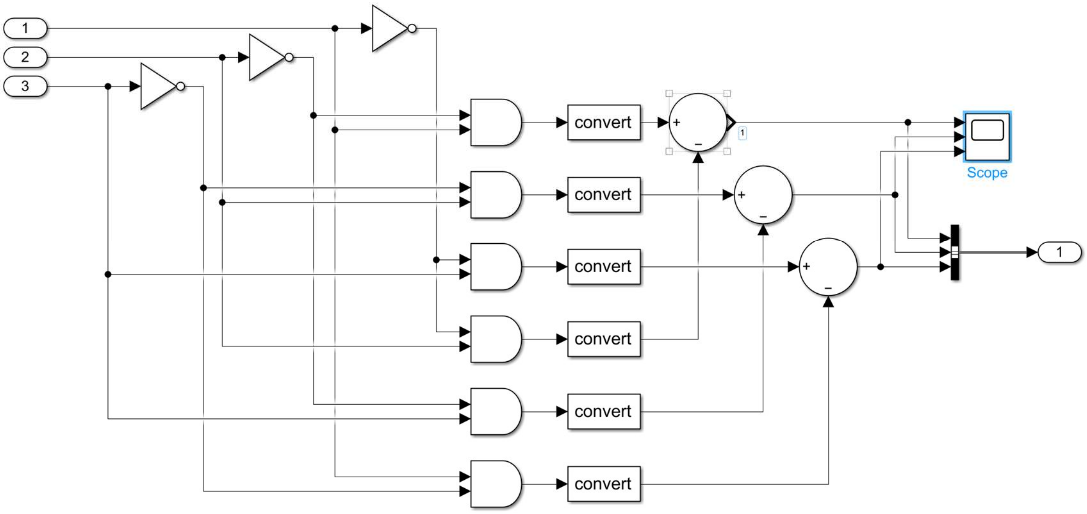

Figure No. 5.3: Hall Sensor Signal Encoder

5.1.1 Hall Effect Sensor

The most common type of rotor position sensor used in BLDC motors is the hall effect sensor. These sensors normally surround the stator and pick up on the magnetic field that the rotor magnets produce. They offer electrical signals that show where the rotor is in relation to the stator windings. Depending on the number of sensors utilised, hall effect sensors can calculate the rotor position with a resolution of 60 degrees or less.

5.1.2 Resolver

A resolver is an electromagnetic device that changes electrical signals from rotor position. It comprises of a stator with windings and a rotor. The resolver can identify the rotor position by supplying an alternating current to the rotor winding and detecting the output voltages from the stator windings. Resolvers are suited for industrial applications because of their high accuracy, resilience, and tolerance to severe environments.

5.1.3 Magnetic Encoders

Magnetic encoders use stationary magnetic sensors positioned all around a revolving magnetic disc that is installed on the motor shaft. The sensors detect changes in the magnetic field while the motor rotates, which enables precise calculation of the rotor location. For more accurate control, magnetic encoders offer higher resolution than Hall effect sensors, generally down to a few degrees or even sub-degree levels.

5.1.4 Optical Encoders

Optically based encoders use a rotating disc with patterns of slots or lines and a stationary optical sensor that detects the breaks in the light created by the rotating disc. Information regarding the rotor location can be gleaned from the quantity and pattern of interruptions.

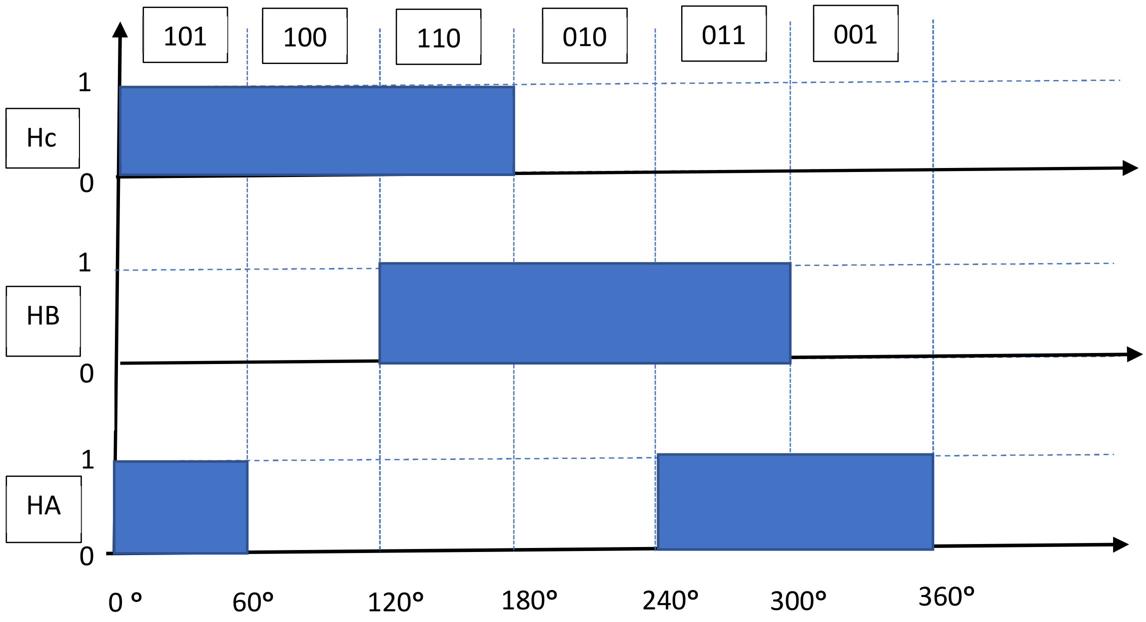

Figure No. 5.4: Hall Sensor Signal Operation

5.2 REFERENCE CURRENT GENERATOR

A reference current generator is a mandatory part of a Brushless DC (BLDC) motor control system that produces the required current references for the motor phases based on the control objectives, such as torque control or speed control. Based on the system's operating circumstances and control strategies, the reference current generator determines the proper current references. The three-phase current amplitude iref is determined by using reference torque Tref

i_ref=T_ref/K_t (5.1)

The currents ia, ib, and ic are three-phase reference currents produced by the reference current generator block based on the position of rotor, and Kt is the torque constant.

The controller of PWM current receives these reference currents as input. The rotor position signal determines the reference current for each phase, which is displayed in Table 5.1.

Table No. 5.1: Rotor Position using Current Reference

Rotor Position ($\emptyset r$)	i_a	i_b	i_c
0-60°	$I_{\_ref}$	- $i_{\_ref}$	0
60-120°	$I_{\_ref}$	0	- $i_{\_ref}$
120-180°	0	$I_{\_ref}$	- $i_{\_ref}$
180-240°	- $i_{\_ref}$	$I_{\_ref}$	0
240-300°	- $i_{\_ref}$	0	i_{ref}
300-360°	0	- $i_{\_ref}$	$I_{\_ref}$

5.3 HYSTERESIS CURRENT CONTROLLER

For Brushless DC (BLDC) motors, a common control method is a hysteresis current controller. It is a closed-loop control system that continuously compares the actual current with a desired reference current to manage the motor current. The objective is to keep the motor operating steadily while minimising the error between the two currents.

The hysteresis current controller functions according to the hysteresis principle, which describes the lagging behaviour displayed by some physical systems. Hysteresis is used in the case of BLDC motors to ensure precise current management by forming a small band around the desired reference current. The hysteresis band or hysteresis window is this band.

Three primary parts make up the hysteresis current controller: a comparator, a current sensor, and a pulse width modulation (PWM) generator.

5.3.1 Current Sensor

The motor windings' real current is monitored by the current sensor. This sensor gives the control system feedback, enabling it to continuously track the current value in real-time.

5.3.2 Comparator

The comparator is in charge of contrasting the required reference current with the actual current. Nothing happens if the actual current stays inside the hysteresis band. The comparator instructs the PWM generator to lower the current if the current exceeds the band’s upper threshold. Similar to this, the comparator instructs the PWM generator to raise the current if the current falls below the lower threshold.

5.3.3 PWM Generator

The pulse width modulation signals used to control the motor drive are produced by the PWM generator. Based on the output of the comparator, it modifies the PWM signals’ duty cycle. The PWM generator lowers the duty cycle to lower the motor current when the actual current reaches the higher threshold. In contrast, the duty cycle is increased to raise the current when the current falls below the lower threshold.

The hysteresis current controller runs in a straightforward on-off mode. The controller immediately acts to reduce the current once it crosses the upper threshold, doing so until it falls within the hysteresis range. Similar to this, the controller reacts quickly to raise the current back into the correct range if it falls below the lower threshold.

The simplicity, quick response time, and resilience of a hysteresis current controller for BLDC motors are some of its main benefits. It provides high dynamic performance by accurately maintaining current control and efficiently suppressing current fluctuations. Due to the rapid on-off switching of the PWM signals, it can produce a substantial amount of switching noise, and it might not perform as efficiently as more sophisticated control approaches like field-oriented control (FOC).

The switching logic Is formulated as given below.

If i_a<(i_a^*-h_b)	Switch 1 ON and switch 4 OFF SA = 1
If i_a<(i_a^*+h_b)	Switch 1 OFF and switch 4 ON SA = 0
If i_b<(i_b^*-h_b)	Switch 3 ON and switch 6 OFF SB = 1
If i_b<(i_b^*+h_b)	Switch 3 OFF and switch 6 ON SB = 0
If i_c<(i_c^*-h_b)	Switch 5 ON and switch 2 OFF SB = 1
If i_c<(i_c^*+h_b)	Switch 5 OFF and switch 2 ON SB = 0

where, hb is the hysteresis band around the three phase's references currents, according to above switching condition of the inverter output voltage are given below:

v_a=1/3[2S A-S B-S C] (5.2)

v_b=1/3[-S A+2S B-S C] (5.3)

v_c=1/3[-S A-S B+2S C] (5.4)

5.4 MODELING OF BACK EMF USING ROTOR POSITION

The PMBLDC motor's phase back EMF is trapezoidal in shape and depends on the rotor position angle and speed, as shown in Fig. 5.2. The phase reverse EMFs can be stated as a result.

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\emptyset_r) \\ f_{bs}(\emptyset_r) \\ f_{cs}(\emptyset_r) \end{bmatrix} \tag{5.5}$$

Where fas(∅r), fbs (∅r) and fcs (∅r) are unit function generators corresponding to the trapezoidal induced emfs of the of BLDCM as a function of fas (∅r) but phase displacement of 120°.

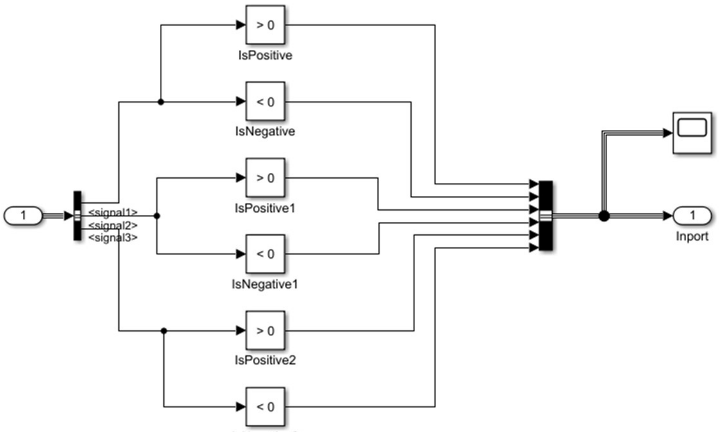

Figure No. 5.5 Logic Decoder from Rotor Positioning Sensor

The back emf functions mathematical model as

$$f_{as}(\emptyset_r) = \begin{cases} \emptyset_r \frac{6}{\pi}, & 0 \le \emptyset_r < \frac{\pi}{6} \\ 1, & \frac{\pi}{6} \le \emptyset_r < \frac{5\pi}{6} \\ (\pi - \emptyset_r)\frac{6}{\pi}, & \frac{5\pi}{6} \le \emptyset_r < \frac{7\pi}{6} \\ -1, & \frac{7\pi}{6} \le \emptyset_r < \frac{11\pi}{6} \\ (\emptyset_r - 2\pi)\frac{6}{\pi}, & \frac{11\pi}{6} \le \emptyset_r < \frac{2\pi}{6} \end{cases} \tag{5.6}$$

$$f_{bs}(\emptyset_r) = \begin{cases} -1, & 0 \le \emptyset_r < \frac{\pi}{6} \\ \left(\emptyset_r - \frac{2\pi}{3}\right)\frac{6}{\pi}, & \frac{\pi}{6} \le \emptyset_r < \frac{5\pi}{6} \\ 1, & \frac{5\pi}{6} \le \emptyset_r < \frac{7\pi}{6} \\ \left(\frac{-5\pi}{3} + \emptyset_r\right)\frac{6}{\pi}, & \frac{7\pi}{6} \le \emptyset_r < \frac{11\pi}{6} \\ -1, & \frac{11\pi}{6} \le \emptyset_r < \frac{2\pi}{6} \end{cases} \tag{5.7}$$

$$f_{cs}(\emptyset_r) = \begin{cases} 1, & 0 \le \emptyset_r < \frac{\pi}{6} \\ \left(\frac{\pi}{3} - \emptyset_r\right)\frac{6}{\pi}, & \frac{\pi}{6} \le \emptyset_r < \frac{5\pi}{6} \\ -1, & \frac{5\pi}{6} \le \emptyset_r < \frac{7\pi}{6} \\ \left(\frac{4\pi}{3} \emptyset_r\right)\frac{6}{\pi}, & \frac{7\pi}{6} \le \emptyset_r < \frac{11\pi}{6} \\ 1, & \frac{11\pi}{6} \le \emptyset_r < \frac{2\pi}{6} \end{cases} \tag{5.8}$$

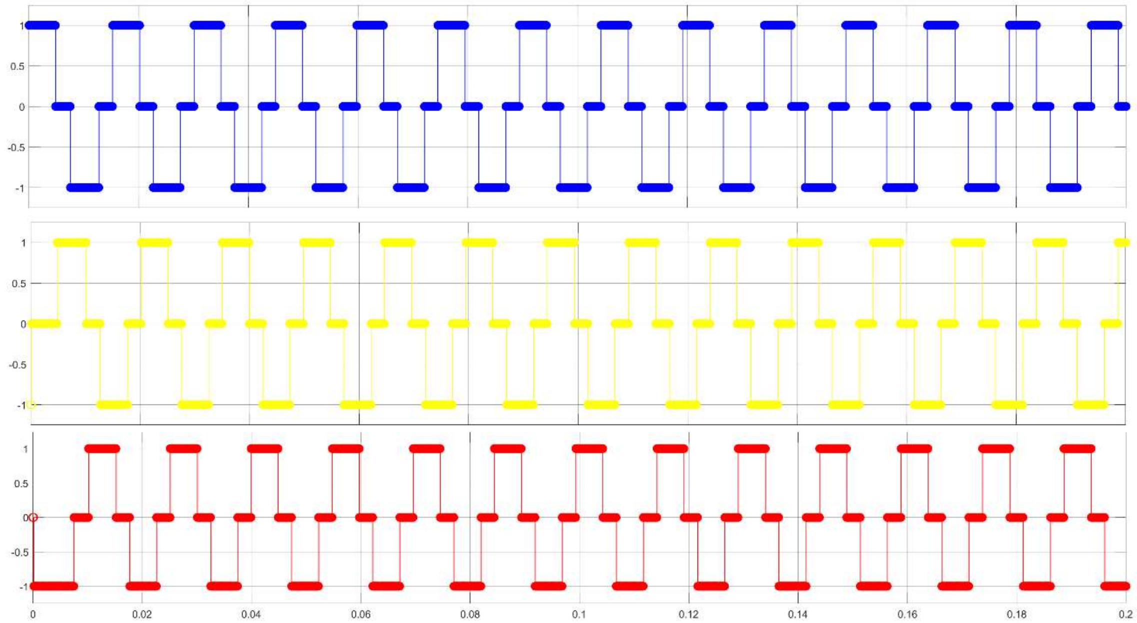

Figure No. 5.6 Logic for Hysteresis Current Controller

CHAPTER 6

DESIGNING OF THE SIMULINK MODEL

There are two control loops for the purpose of controlling brushless DC motor speed. The inner loop is used to synchronise the gate pulse of the inverter with the EMF, while the other loop is utilised to modify the direct current bus voltage to control speed. An important occurrence occurs when the motor winding current reverses direction during the reset phase of a device. In this case, the current flows in the same direction and passes through the freely rotating diodes. By directly feeding a proportional component of the reference speed into the voltage-controlled voltage source, we further attempt to use the property of BLDC motors having a specific KV rating per motor. This enables the system to attempt to reach the reference speed automatically. We just attempt to reduce the difference produced in the startup and loading/unloading situations by using the feedback loop with the PID controller in an additive parallel configuration.

The PID controller block from MATLAB Simulink is used in this work as a digitally electronic PID controller. PID can be converted to a proportional integral and proportional integral derivative controller by simply changing its settings. The enormous array of speed response signals are then evaluated after proportional integral and proportional integral derivative controllers are simultaneously implemented in the forward direction of the brushless DC model.

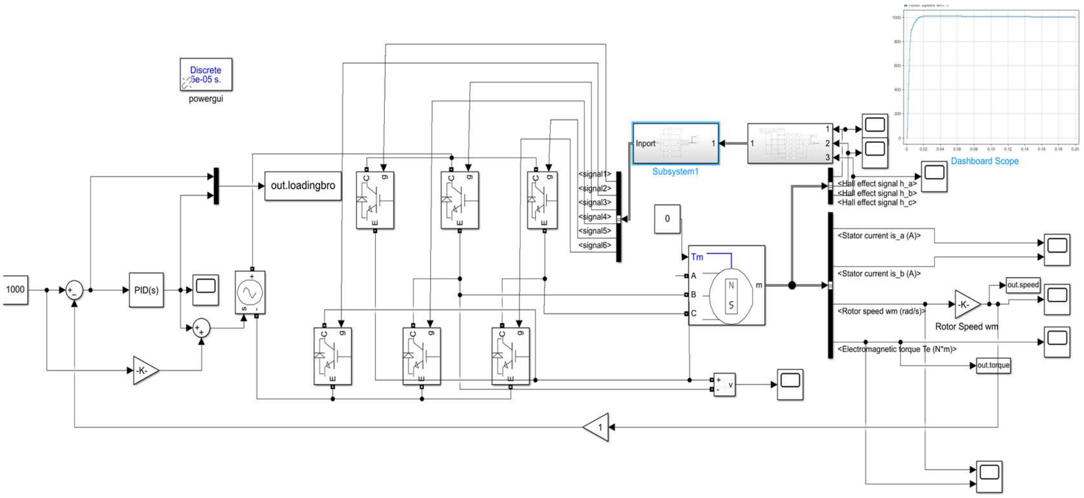

Figure No. 6.1 Simulation Model for BLDC Motor Controlling

To estimate real-world models, we restrict the precision of the Kp, Ki, and Kd parameters as well as the filter coefficient (N) utilised in the PID controller to no more than four digits after the decimal.

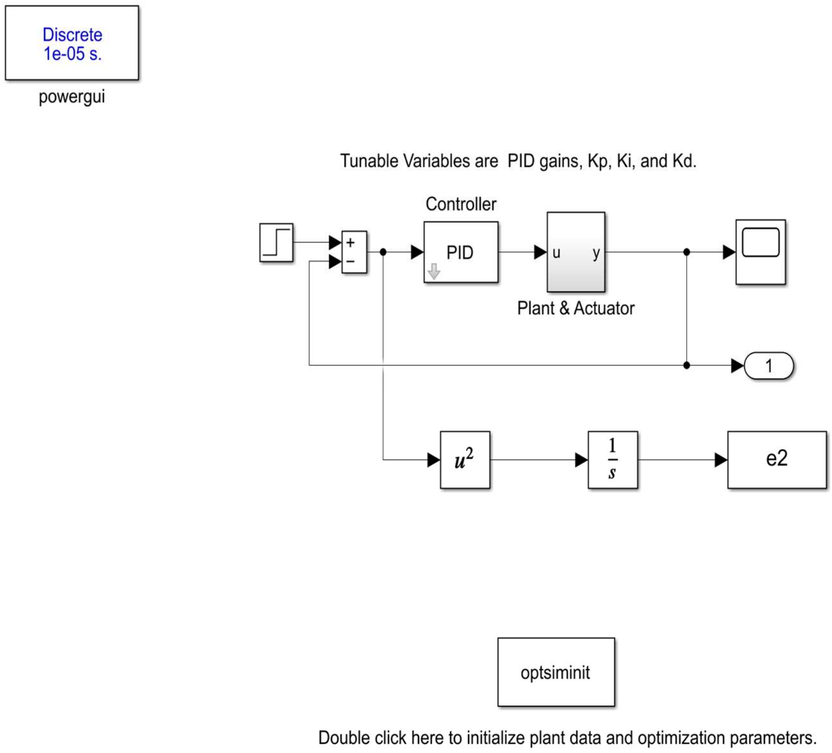

Figure no. 6.2 Simulation Modelling for Intelligent Controlling of BLDC Motor

To identify the most effective parameters for both PI and PID controllers, the controllers were tuned using the hit-and-trial approach, the PID tuner offered by MATLAB, and the PSO technique as described in. The MSE (Mean Squared Error) method and optimisation of the Kp, Ki, and Kd parameters for the controller were used to modify by the PSO algorithm. The PSO algorithm was run 1000 times with C1 and C2 learning rates, and the top performing parameters were used to produce the final results.

CHAPTER 7

RESULTS AND DISCUSSIONS

using the manual, auto-tune, and PSO algorithms, the behaviour of the BLDC motor has been evaluated over a range of proportional, derivative, and integral coefficient values. The outcomes and graphs that follow highlight the best values. PID values have various different relationships with one another.

The behaviour of a BLDC motor in relation to speed is shown in the accompanying figures, along with details on how it reaches steady state and with the aid of a controller. The speed is compared with the reference speed with the aid of a controller, which computes the error from the reference speed using feedback from the controlled parameter and generates a control signal to reduce this error based on proportional and integral terms of the error signal.

7.1 PERFORMANCE WITH PI CONTROLLER

PI Controller can obtain the desired speed response, minimise overshoot, and minimise steady-state error by adjusting the proportional and integral gains of the controller. Higher integral gains assist to decrease steady-state error but may result in instability if set too high. Higher proportional gains boost the controller's reactivity but may induce overshoot.

Overall, by providing precise speed or position control and reducing steady-state errors, a correctly tuned PI controller can improve a BLDC motor's performance. However, the precise tuning parameters may necessitate experimentation and fine-tuning because they depend on the motor's properties, the dynamics of the load, and the intended performance standards.

7.2 PERFORMANCE WITH PID CONTROLLER:

PID controller is used to maintain the desired speed of the motor. Feedback from the motor of rotor speed in terms of degrees per second is used.

The controller is tuned using trial and error basis until a stable output is achieved and then it is achieved with the help of PSO and compared with the previous results. The

PID controller actuates the controlled voltage source to adjust the voltage to the universal bridge and in turn on the BLDC.

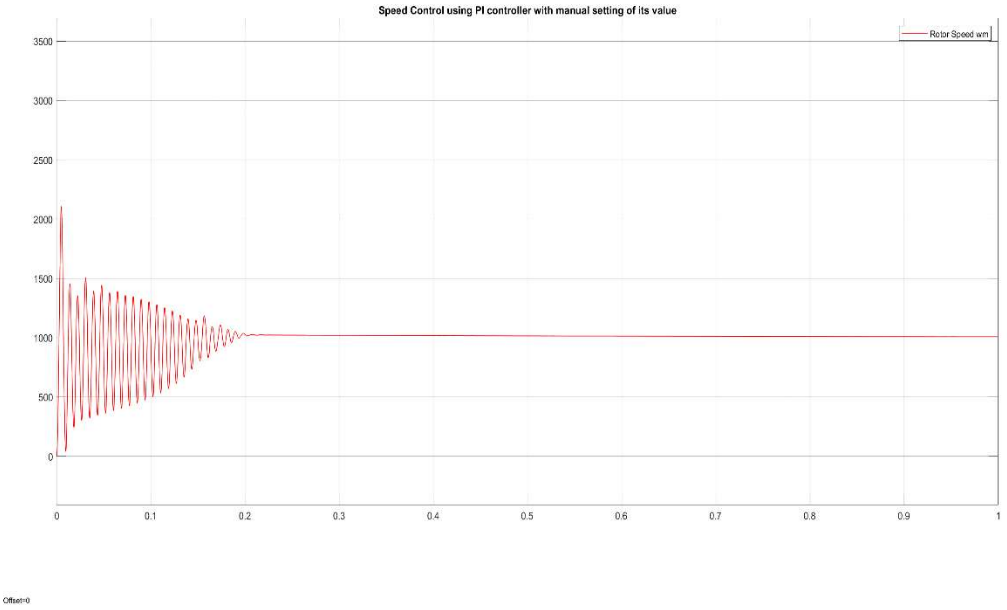

Figure No. 7.1: Speed Control of BLDC Motor using PI Controller by Manually Setting the values

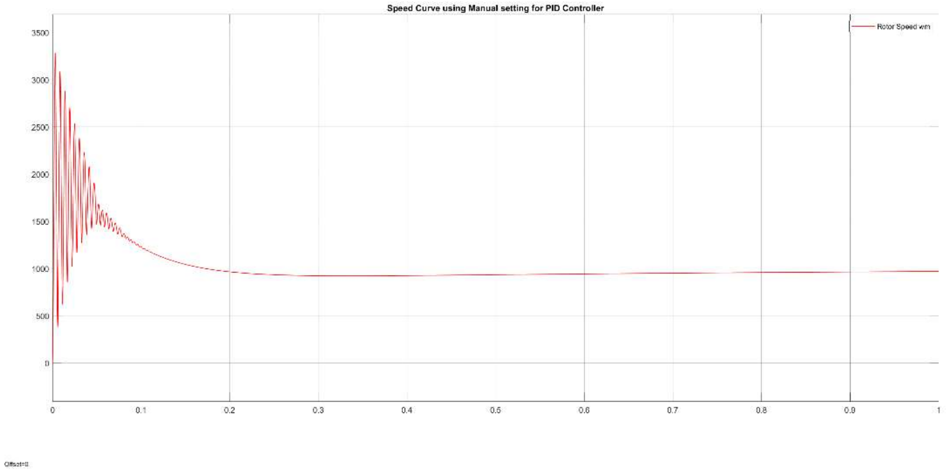

Figure No. 7.2: Speed Control of BLDC Motor using PI Controller by Manually Setting the values

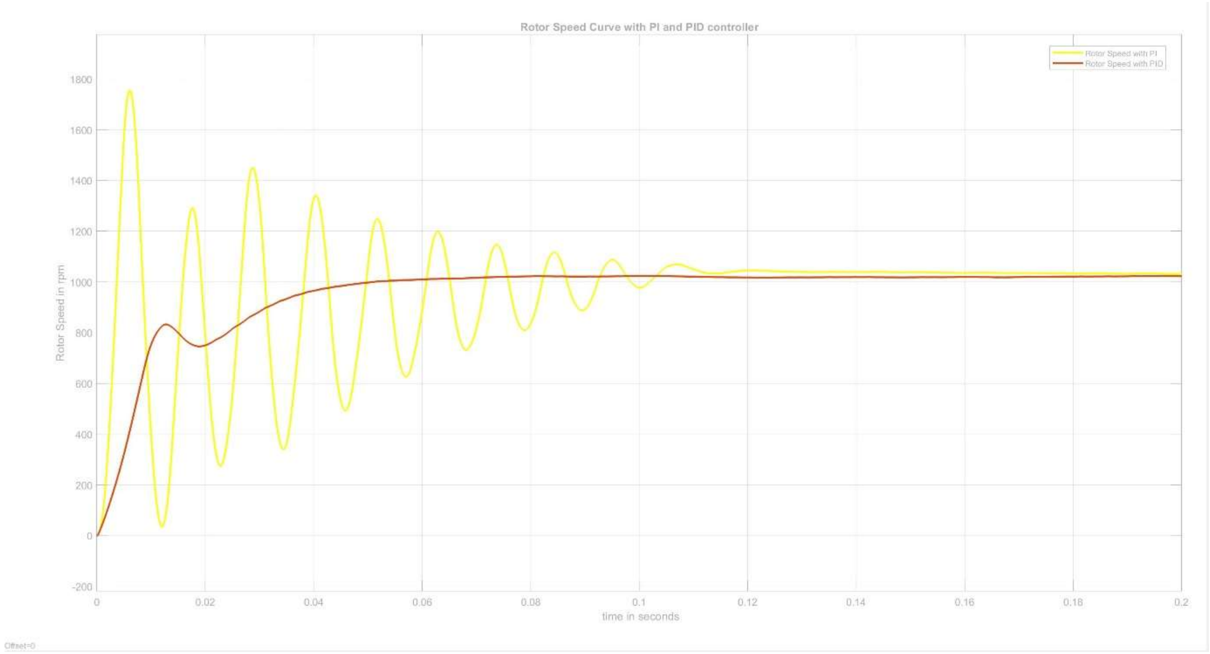

Figure No. 7.3: Comparison of PI and PID when derivative parameter is low

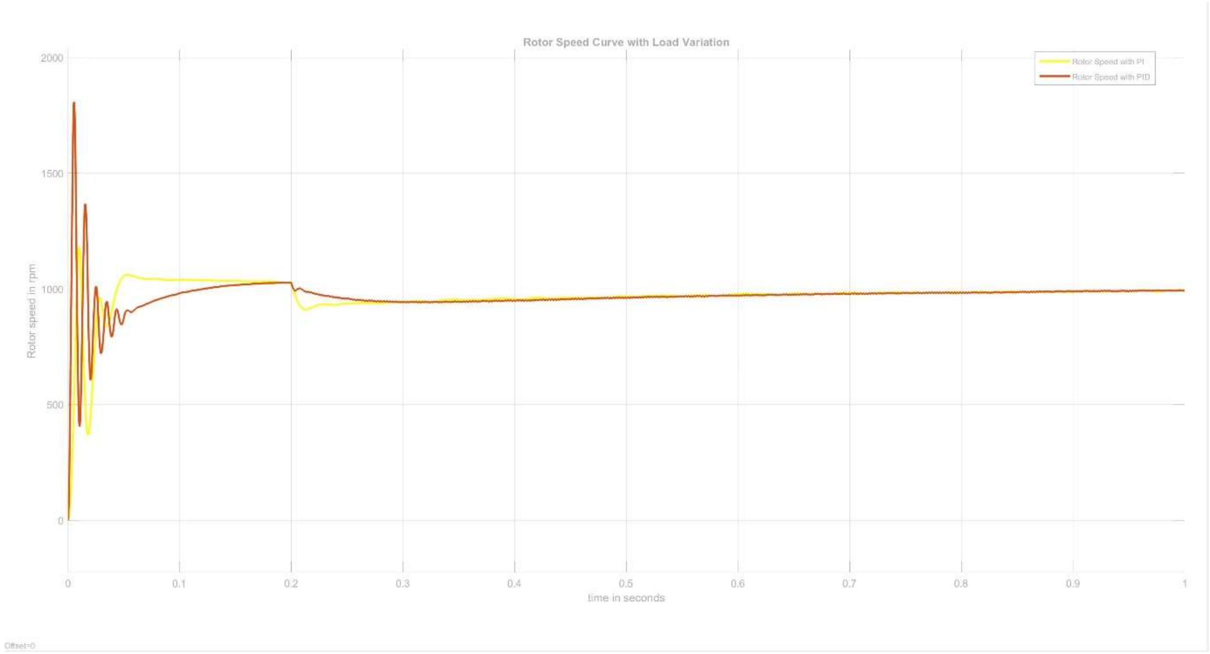

Figure No. 7.4: Behaviour of PI and PID Controller, When load is provided to the BLDC Motor at 0.2 seconds

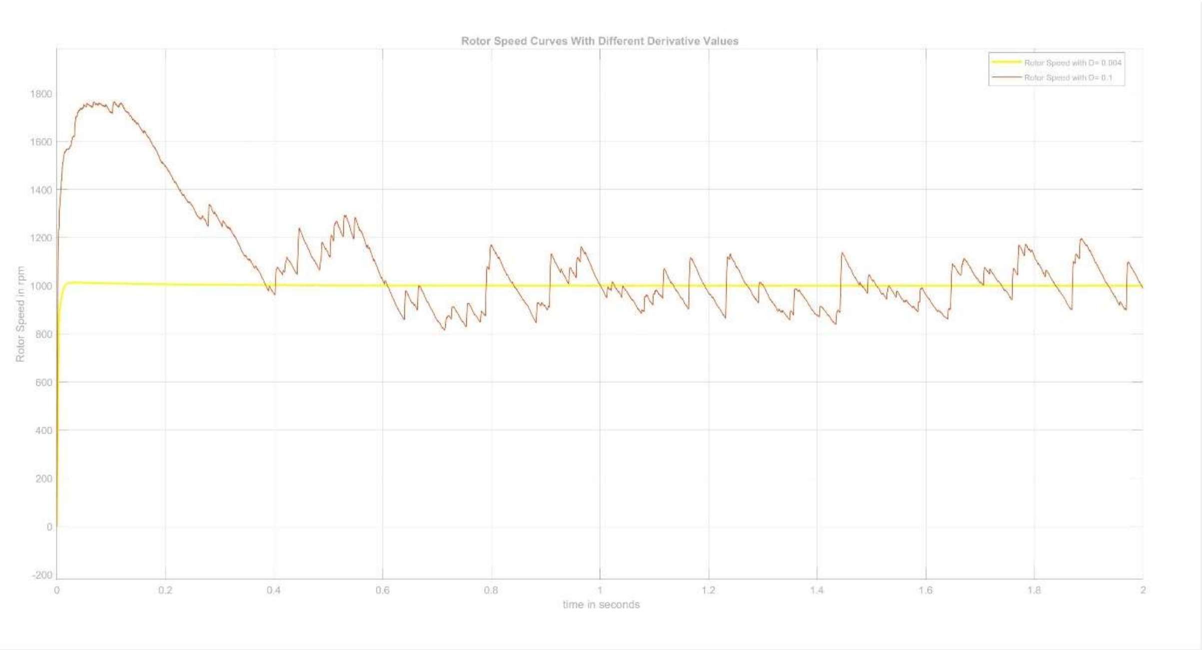

Figure No. 7.5: Speed Controlling with different values of Derivative Constant

7.3 ELECTROMAGNETIC TORQUE OF PID CONTROLLER

Accurate and steady position control can be achieved by adjusting the gains of the proportional and integral terms. Similar to speed control, greater integral gains assist decrease steady-state error but might produce instability if set too high. Greater proportional gains boost the controller’s reaction but may also introduce overshoot.

Overall, by providing precise speed or position control and reducing steady-state errors, a correctly tuned PI controller can improve a BLDC motor’s performance. However, the precise tuning parameters may necessitate experimentation and fine-tuning because they depend on the motor’s properties, the dynamics of the load, and the intended performance standards.

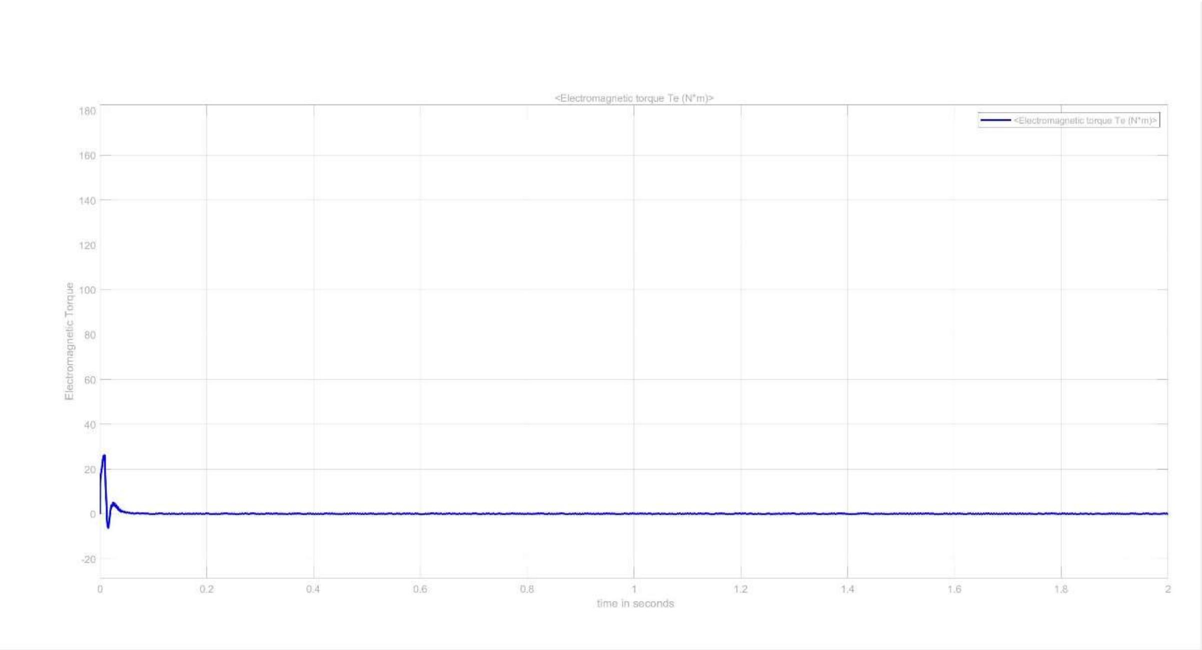

Figure No. 7.6: Electromagnetic Torque tunning the parameter of the PID

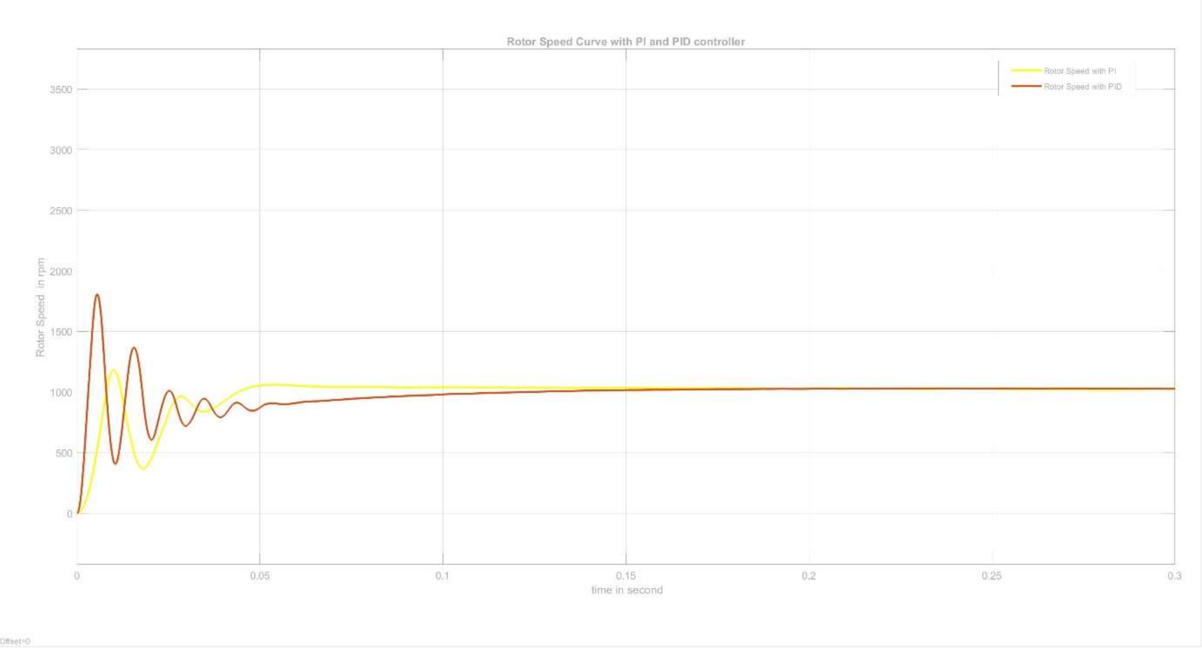

Figure No. 7.7: Speed Control of the BLDC Motor using PSO Motor

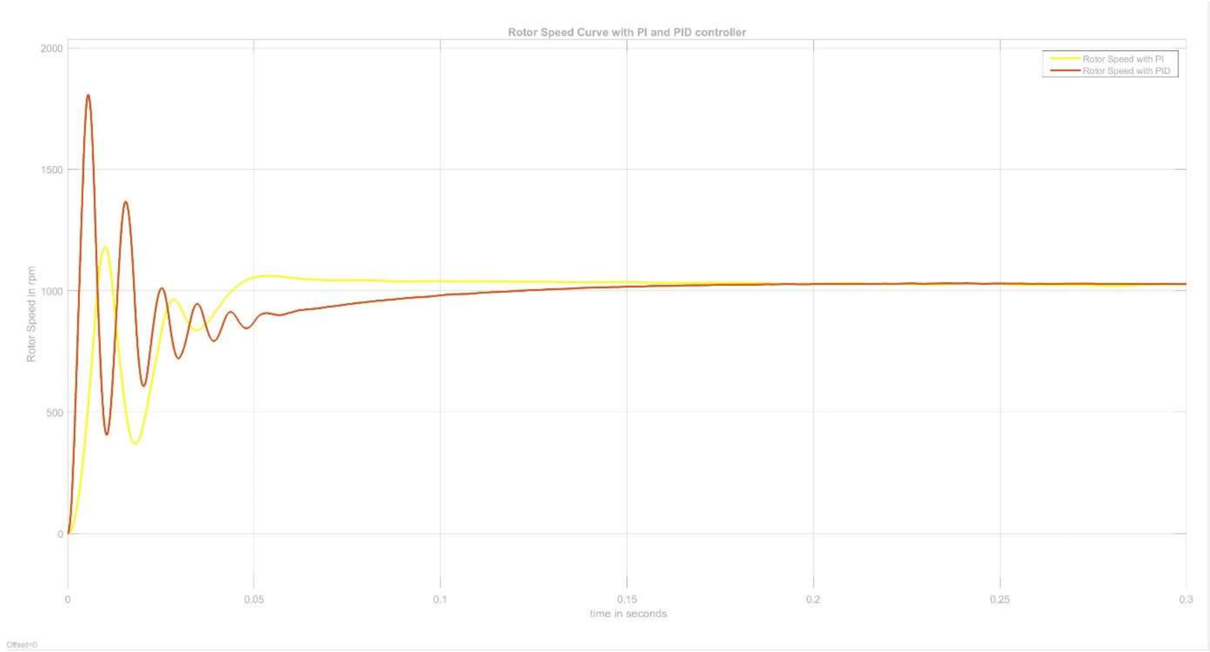

Figure No. 7.8: After tunning the value of PI and PID parameter using PSO Algorithm, Kd to 0.3

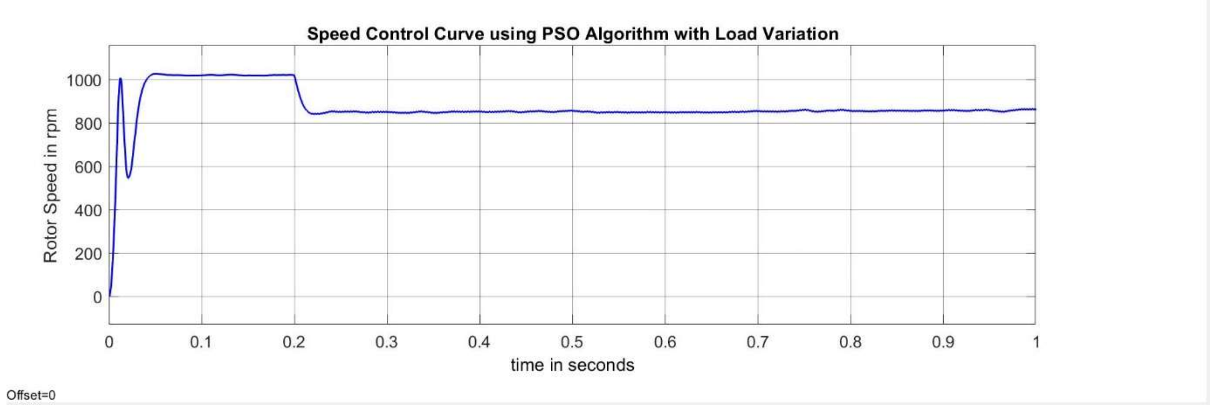

Figure No. 7.9: Load variations at 0.2 second

Figure 4.4 displays the outcome of the PSO Algorithm's Load Variation at the 0.2-second mark of a 1-second period. When load is applied, Speed's nature is revealed.

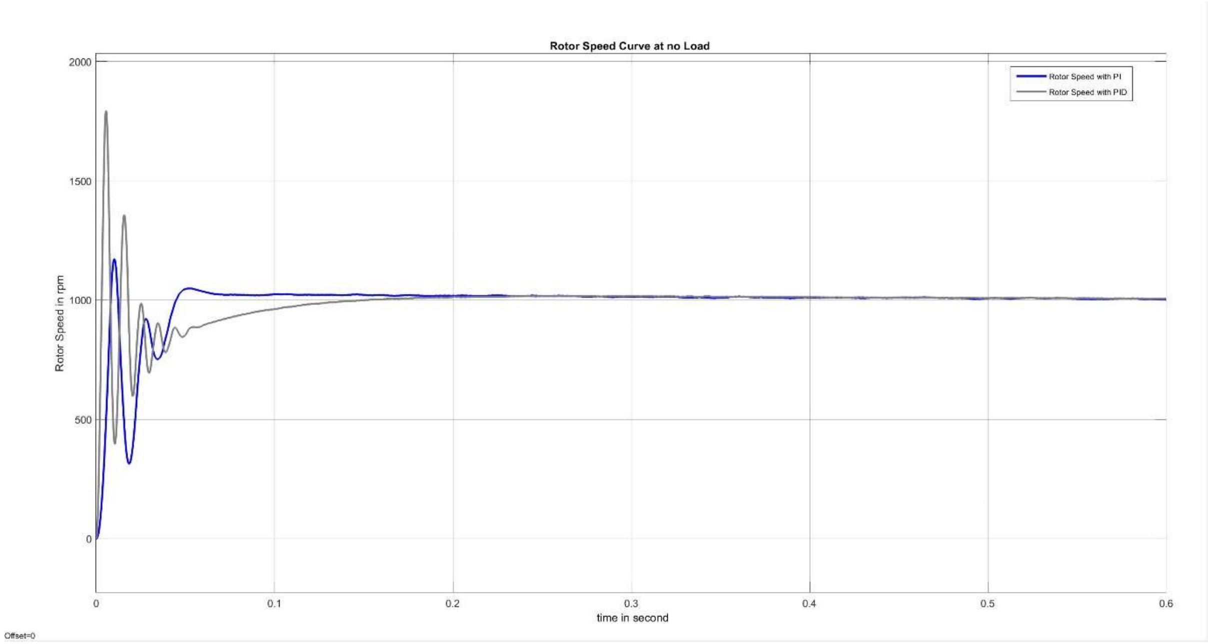

Figure No. 7.10: Settling time is less for PI Controller

Figure 7.10 depicts the behaviour of a motor controlled by a PI or PID controller when there is no load. It highlights the various settling times and oscillations for the two speed curves. We are aware that the contribution of Kp and Ki causes the overshoot to increase while the rising time to decrease.

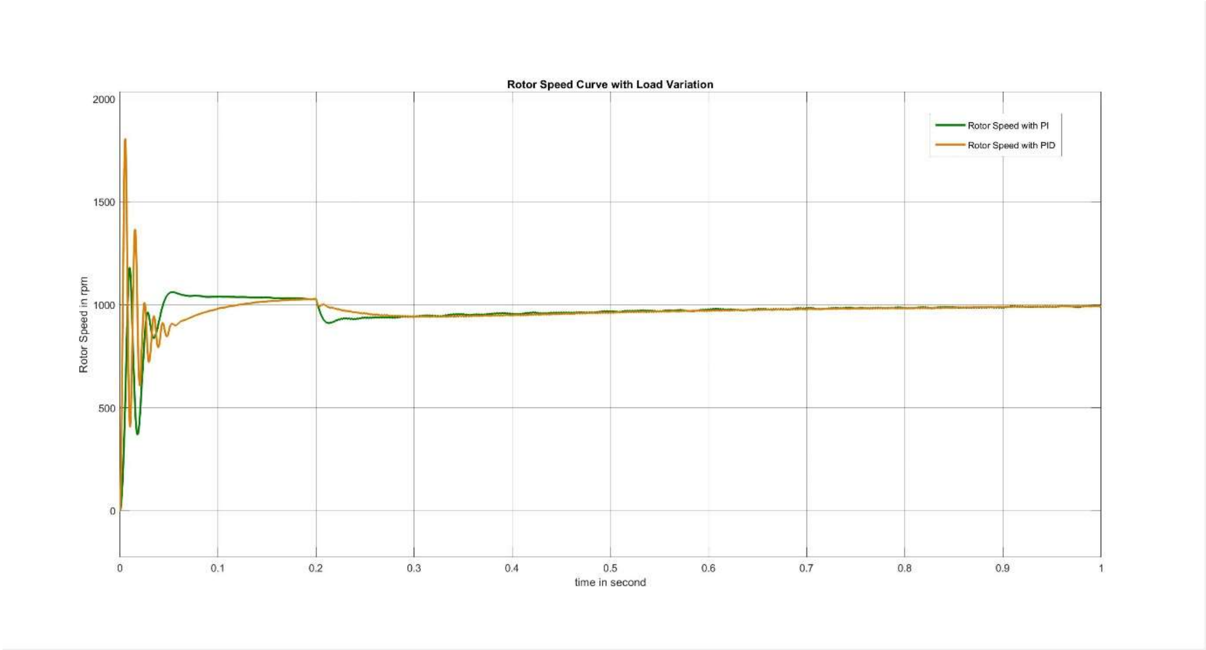

Figure No. 7.11: When Load is provided at 0.2 seconds, PID Controller takes less variation

Figure 7.11 depicts the characteristics of the PI and PID controller speed curves, with the PI controller settling for 0.05 seconds and the PID controller applying load for 0.2 seconds. Both controllers behave virtually identically, although the PI controller exhibits a decrease in speed. then quickly adjusts to the speed rather than gradually.

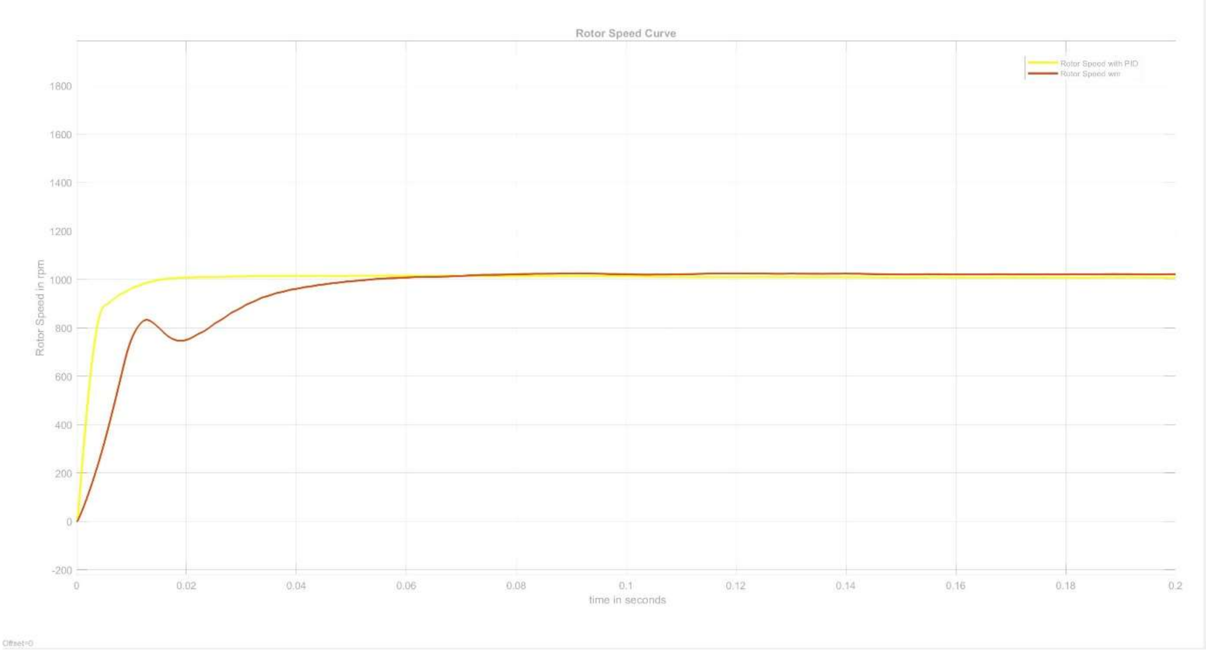

Figure No. 7.12: Using PSO, PI and PID Controller Comparison

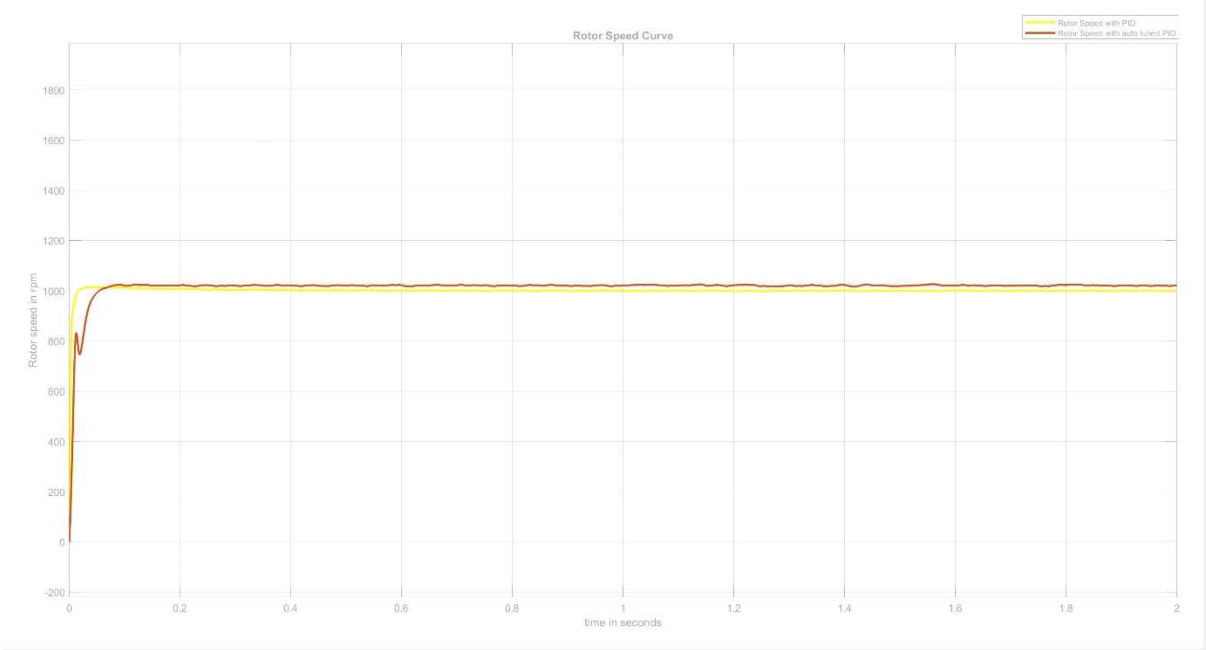

Figure No. 7.13: Smooth Speed Controlling of BLDC Motor using PSO Algorithm

Table No. 7.1: For PI Controller:

Parameters Setting Method	Settling Time (seconds)	Maximum Peak Value (rpm)
Manual Setting	0.055	1172
Auto Tuned	0.05	1060
PSO Algorithm	0.045	1057

Table No. 7.2: For PID Controller:

Parameters Setting Method	Settling Time (seconds)	Maximum Peak Value (rpm)
Manual Setting	0.14	1793
Auto Tuned	0.06	985
PSO Algorithm	0.05	1007

These findings demonstrate that when the PID controller and PI controller are optimised with the PSO method and the first overshoot does not exceed the permitted amount, the speed controlling settle time is reduced.

Based on the parameters setting procedure, the results are shown in a table along with a summary of the PI and PID controller's associated settling times and peak values.

CHAPTER 8

CONCLUSIONS

8.1 CONCLUSIONS:

The followings are the conclusions of this project work:

1. In this work two controllers have been implemented on BLDC motor. The parameters of this controllers have been optimised using PSO Algorithm in MATLAB Simulink.
2. PID controller handled loading and unloading the motor more elegantly by presenting a progressive change in speed rather than an abrupt change in speed, usually peak values goes very high when we change the load and does not optimise the value for controller, the maximum peak value of speed obtained with PI controller using manual setting was 1172 rpm and 1793 rpm for PID controller when these parameters are optimised using PSO algorithm, maximum peak value reduced to 1057 rpm for PI controller and 1007 rpm for PID controller which shows that with PSO algorithm controller we have optimised the result in terms of maximum peak value.
3. When the PID controller and PI controller are optimised with the PSO method, the settling time was reduced. The settling time for PI controller using PSO is 0.045 seconds and for PID controller it is 0.05 seconds.
4. When a derivative component is added to the motor, the motor oscillates more and amplitude wise adds up to the more than 50% of the magnitude. This behaviour can be understood by the fact that BLDC motors produce pulsations in the torque rather than a constant amount of torque due to the electronic commutation brought on by the IGBT. The derivative component, which generates significant output depending on the high frequency micro-oscillations occurring in the motor speed, amplifies this pulsating effect.
5. When the motor is running with the speed of 1000 rpm and we provide the load at 0.2 seconds then PID controller does not deviate rapidly, it deviates gradually in comparison of PI controller hence PID controller is more suitable in sudden load change applications of BLDC motor.

8.2 FURTHER WORK

For robotic manipulators powered by brushless dc motors and with arbitrarily unknown inertia and electrical parameters of the actuators, the hybrid integrator back stepping controller is suggested.

The study of robot control, on the other hand, was very recently discovered. It was suggested to use a robust feedback linearizing control. Robust and adaptive controllers are suggested employing integrator back stepping approaches, respectively. However, it should be highlighted that all of those results are only appropriate for an inertial load (a single-link manipulator).

The goal of this project is to create a control strategy for a stiff n-link manipulator with BLDCM-driven joint actuators. A hybrid integrator backstepping controller (i.e., adaptive and robust adaptive) is suggested based on integrator backstepping approaches. These characteristics apply to the proposed controller:

- Joint acceleration feedback is not necessary.

- A semiglobal asymptotic stability solution is obtained in the Lyapunov sense without the need for knowledge of the robot or any of the BLCDM uncertain parameters.

PUBLICATIONS:

Yashi Rani, Uma Nangia and N.K. Jain, “Implementation of PSO Based Controllers for Speed Control of BLDC Motor,” 2023 IEEE 4th International Conference of Emerging Technologies. (INCET 2023), Belgaum, India. (Yet to be Published) – Accepted

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