HYBRID FUZZY- PROPORTIONL INTEGRAL DERIVATIVE CONTROLLER (F-PID-C) FOR CONTROL OF SPEED BRUSHLESS DIRECT CURREN MOTOR (BLDCM)

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Dedicated with gratitude to my country Libya for the huge support and giving me this opportunity to study overseas.

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ABSTRACT

Hybrid Fuzzy proportional-integral-derivative (PID) controllers (F-PID-C) is designed and analyzed for controlling speed of brushless DC (BLDC) motor. A simulation investigation of the controller for controlling the speed of BLDC motors is performed to beat the presence of nonlinearities and uncertainties in the system. The fuzzy logic controller (FLC) is designed according to fuzzy rules so that the systems are fundamentally robust. There are 49 fuzzy rules for each parameter of FUZZY-PID controller. Fuzzy Logic is used to tune each parameter of the proportional, integral and derivative (k_p, k_i, k_d) gains, respectively of the PID controller. The FLC has two inputs i.e., i) the motor speed error between the reference and actual speed and ii) the change in speed of error (rate of change error). The three outputs of the FLC are the proportional gain, k_p, integral gain k_i and derivative gain k_d, gains to be used as the parameters of PID controller in order to control the speed of the BLDC motor. Various types of membership functions have been used in this project i.e., gaussian, trapezoidal and triangular are assessed in the fuzzy control and these membership functions are used in FUZZY PID for comparative analysis. The membership functions and the rules have been defined using fuzzy system editor given in MATLAB. Two distinct situations are simulated, which are start response, step response with load and without load. The FUZZY-PID controller has been tuned by trial and error and performance parameters are rise time, settling time and overshoot. The findings show that the trapezoidal membership function give good results of short rise time, fast settling time and minimum overshoot compared to others for speed control of the BLDC motor.

ABSTRAK

Pengawal (F-PID-C) Hibrid Kabur berkadaran-kamiran-terbitan (PID) direka dan dianalisis bagi mengawal kelajuan motor DC (BLDC) tanpa berus. Suatu penyiasatan simulasi bagi pengawal yang mengawal kelajuan motor BLDC dijalankan untuk menghalang kewujudan ketidaklinearan dan ketidakpastian di dalam sistem. Pengawal logik kabur (FLC) direka berdasarkan peraturan kabur supaya sistem-sistem teguh pada dasarnya. Terdapat 49 peraturan kabur bagi setiap parameter pengawal FUZZY-PID. Logik kabur digunakan untuk menala setiap parameter bagi gandaan-gandaan berkadaran, kamiran dan terbitan (k_p, k_i, k_d), masing-masing bagi pengawal PID. FLC mempunyai dua input iaitu, i) ralat kelajuan motor antara rujukan dan kelajuan sebenar, dan ii) perubahan dalam kelajuan daripada ralat (kadar bagi ralat perubahan). Tiga output daripada FLC iaitu gandaan berkadaran; k_p, gandaan kamiran; k_i dan gandaan terbitan; k_d, gandaan-gandaan akan digunakan sebagai parameter bagi pengawal PID dalam mengawal kelajuan motor BLDC. Pelbagai jenis fungsi keahlian telah digunakan dalam projek ini seperti Gaussan, trapezoid dan bersegi tiga dinilai dengan kawalan kabur dan fungsi keahlian ini digunakan dalam FUZZY PID bagi analisis perbandingan. Fungsi-fungsi keahlian dan peraturan-peraturan telah ditakrifkan menggunakan editor sistem kabur yang diberi dalam MATLAB. Dua situasi yang berbeza telah disimulasikan, iaitu sambutan mula, sambutan langkah dengan beban dan tanpa beban. Pengawal FUZZY-PID telah ditala dengan kaedah cuba-cuba dan prestasi parameter, iaitu masa naik, masa pengenapan dan lajakan. Dapatan menunjukkan fungsi keahlian trapezoid memberikan keputusan baik bagi masa naik yang pendek, masa pengenapan yang pantas dan lajakan minimum dibandingkan dengan yang lain-lain bagi kawalan kelajuan motor BLDC.

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LIST OF SYMBOLS AND ABBREVIATIONS

BLDCM - Brushless Direct Current Motor
FLC - Fuzzy Logic Controller
PID - Proportional Integral and Derivative
F-PID-C - Fuzzy- Proportional Integral and Derivative- Controller
EMF - Electromotive Force
PSO - Particle swarm optimization
MF - Membership Functions
DC - Direct Current
AC - Alternative Current
PMSM - Permanent Magnet Synchronous Motor
PWM - Pulse Width Modulation Techniques
T_P - Peak Torque
T_R - Rated Torque
SISO - Single-Input-Single-Output
MIMO - Multi-Input-Multi-Output
C_1 - Controller
C_2 - Plant
Z - Sensor
$C_1(s)$, - Transfer Function Elements
$C_2(s)$, - Transfer Function Elements
$Z(s)$ - Transfer Function Elements
$y(t)$ - The Measured Output)
$r(t)$ - The Desired Output
$e(t)$ - Tracking Error
k_p - Proportional Gain
k_i - Integral Gain
k_d - Derivative Gain

$C(s)$ - Correcting Terms

$MV(t)$ - Manipulated Variable

P_{out} - Output Proportional Term

I_{out} - Output Integral Term

D_{out} - Output Derivative Term

τ - A dummy Integration Variable

t - Time or Instantaneous Time

V_{al3} V_{al1} - Membership Boundaries of Triangular

V_{al2} - Membership Boundaries of Triangular

V_{al1}, V_{al3} - Membership Boundaries of Trapezoidal

V_{al2}, V_{al4} - Membership Boundaries of Trapezoidal

X_p - The Midpoint

w - The Width of Bell Function

$\mu(u_i)$ - Bell Membership Function

P_B - Positive Big

N_B - Negative Big

N_S - Negative Small

Z - Zero

N_M - Negative Medium

P_S - Positive Small

P_M - Positive Medium

MAX - Max Criterion Method)

COA - Centroid Method or Center of Area Method

U_o - Final Output

v_{bs},v_{cs}, - Phase Voltages

R_a, R_b, R_c - Stator Resistance Per Phase

i_a, i_b i_c - Stator Phase Currents

e_a , e_b e_c - The Phase Back Electromotive Forces

L_{ab}, L_{bc} - Mutual Inductances Between Phases a, b and c

D - Differential Operator

T_e - Electromagnetic Torque (N ·m)

ω - Motor’s Mechanical Angular Velocity (rad/s)

n_p - Rotor Pole Pairs.

T_l - Load Toque

J - Rotor Moment of Inertia

R_N - Number of Rules =, and =

M - Number of Membership Functions

N - Number of Inputs

Ce - Change of Error

e - Error

t_s - Settling Time

m_p - Rise Time

t_r - Overshot

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CHAPTER 1

INTRODUCTION

1.1 Background

Motor drives with high performance efficiency are vital in several industries and have found application in many areas such as electric automotive, robotics, rolling mills, aviation, electric trains, and robotics [1]. Electric motors in different forms have been suggested for use in applications [2], among which the DC motors stands out. Contrarily, there are several disadvantages of the conventional DC motor, including the need for a routine maintenance of the commutators, high initial cost, and frequent changing of the brushes [3].

The conventional DC motors are not ideal in explosive or clean environments. An alternative to the DC motor is the Squirrel cage induction motor which more robust and commands an initial low cost. Meanwhile, a low power factor and starting torque are the major problems of the Squirrel cage induction motor [4]. Additionally, both the induction and conventional DC motors are not suitable for high-speed use. Another alternative to the DC and induction motors for high speed application is the brushless DC motors. The brushless DC motor is notorious for high speed usage [4]. There are several advantages of the BLDC motors over brushed DC motor; these include having longer life, immunity to noise, higher efficiency, relatively small, requiring less maintenance since there are no brushes, and commutator arrangement. The BLDC, as the name suggests, uses electronic commutation for commutation instead of brushes, which makes it a virtually [5]. There are other advantages of the BLDC motor over the induction motor, including having a better speed - torque characteristics, longer operating life, high dynamic response, and operating noiselessly, which made it a dominant electric motor [6].

1.2 Problem statement

BLDC motors require suitable speed controllers to accomplish desired level of performances. Normally, proportional integral and derivative (PID) controller is used for the control of the speed. Though the conventional PID controllers are mostly used industrially owing to the simple structure of their operation and ease of implementation, they pose problems in the presence of control technique like sudden change in setpoint and, parameter variation (k_p,k_i,k_d) not produce automatically and these parameters need to tune, it makes the PID control gives poor response, and nonlinearity, the non-linearity arises due to armature current limitation and change in loads. Furthermore, the PID controller is difficult to tune the parameters and get satisfied control characteristics [7].

Being that BLDC motors have nonlinear model, the PID controllers are not ideal to be used. In addition, traditional PID controller cannot be used in systems with unstable parameters because the PID constant will be required to be changed often [4]; also, the BLDC motor may cause serious overshoots because it has high start torque which are not desired in most conventional controllers like PID. In this way, the BLDC motor drives system need appropriate controllers like the fuzzy PID controllers (F-PID-C) to govern the startup response, decrease overshoot and steady-state error to meet the system demands [8].

The F-PID-C is an extension of the conventional technique because of its maintenance of the linear structure of PID controllers. The F-PID-C was designed based on the basic F-PID-C principle to achieve a good controller with analytical formulas like the other smart controllers. The F-PID-C has variable control gains within their linearity structure which are nonlinearity functions of the error and the rate of changes in the error signals. They can improve the overall performance of the

BLDC motor owing to their characteristic features such as the self-tuned mechanisms which can adjust to error variations and rate of error changes caused by time delay, nonlinearity and process uncertainties [9].

In this research, three types of membership functions (MF) of F-PID-C model for the control of BLDC motor will be designed and compared between each other to achieve the best model.

1.3 Research Objectives

The study objectives are:

i. To analyze the transient characteristics of BLDC motor, i.e., by overshot amplitude, steady-state error and rise time using Fuzzy-PID controller based on three types of membership functions, i.e., Gaussian, Trapezoidal and Triangular.

ii. To compare between three different types of MF by Fuzzy PID control on the BLDC motor.

iii. To compare between two controller Fuzzy-PID controller and Fuzzy-PI controller

1.4 Scope of Project

i. Using Simulink in MATLAB to implement fuzzy PID controller to control the speed of the BLDC motor.

ii. Design three type of Membership functions and rules using Fuzzy Toolbox in MATLAB.

iii. Simulation of the BLDC motor model on a MATLAB Simulink platform and developed FLC system.

CHAPTER 2

FUZZY-PID CONTROLLER CONCEPT AND BLDC MOTOR ASPECTS REVIEW

2.1 Introduction

This chapter describes the literature review of BLDC motor, PID controller and Fuzzy logic control system. In this chapter, also will discuss some researches that are relevant to this project to demonstrate continuity from the previous researches.

2.2 Previous case study

The speed and current controllers of BLDC motor with non-sinusoidal (trapezoidal) back-electromotive force have been investigated previously [10]. Faster drives with reduced ripples in current and torque and smoother speed response are often desired. In many applications, BLDC motors are controlled using back EMF. This work implements a simple control scheme which have no need any complicated calculation, or knowing the back EMF and shape functions. To address the issues of the conventional PID speed controllers, the Fuzzy logic speed controller is being set forth for the reduction of the starting current, elimination of torque overshoot, and achieving a fast speed response. The design is simple and does not require any complex computation. Simulation studies were conducted to validate the effectiveness of the proposed system in controlling the performance of BLDCM. A robust control was achieved with the proposed algorithm via MATLAB simulation.

An adaptive F-PID-C for controlling the speed of DC brushless motor has a wide industrial application, such as in the servo motor drives, automobile, medical, and aerospace has been studied [11]. There are many advantages of the electronically commutated BLDC motors over the brushed DC motor, such as having longer life, lower volume, increased efficiency, and higher torque. This study employed Simulink model to analyze the performance of F-PID-C and adaptive F-PID-C. The tuning and computation of parameters using the normal PID controllers is difficult and when compared to the adaptive fuzzy PID controllers, does not produce satisfactory control features. The simulation studies verified a better performance of the adaptive F-PID-C compared to the F-PID-C. The BLDC motor was modelled and controlled using the SIMULINK software package.

A new P-fuzzy self-adaptive PID intelligent method based on the BLDC motor mathematical model has been proposed [12] for the control of the speed of a servo system. In the BLDC motor control system, current hysteresis is applied in the current loop, while the P and fuzzy self-adaptive PID hybrid control scheme is applied in the speed loop. To organically combined the blocks, a double close loops timing system with current hysteresis and fuzzy speed control was tested and the simulation results showed that the system has an improved accuracy, reduced response time, controlled overshoot, achieved fine robustness, was self-adapting, and obviously performed better compared to the ordinary proportional-integral, differential (PID) control. The model was validated and verified, and thus, a novel approach was provided for further motor studies.

An optimized fuzzy logic controller based on the particle swarm optimization (PSO) for the control of DC motor speed has been proposed [13]. The simulation of the controller model was carried using MATLAB software and tested on a laboratory DC motor experimentally. The performance of several controllers such as fuzzy logic controllers, PID controllers, and optimized fuzzy logic controllers was compared as well. Simulation and experimental results showed that the suggested fuzzy logic control (FLC) and PSO speed controllers had better dynamic performance compared to the normal FLC and PID controllers. Furthermore, it had a better performance on the DC motor with a perfect speed tracking devoid of overshoots. With heuristically defined MF, the optimized membership functions (MF) offered a better performance and higher robustness compared to the regular fuzzy model. Furthermore, the ability of proposed FLC under sudden load torque changes which can result in speed variances was experimentally verified.

2.3 Brushless direct current motors (BLDC)

Several applications demand electric motors with a range of speed and torque control and the DC machine met these criteria though it needs a periodic maintenance. Like the induction and brushless permanent magnet motors, the AC machines have no brushes and are designed with robust rotors due to the absence of a commutator and/or rings, meaning a very low maintenance is required. The efficiency and power-to-weight ratio are also enhanced by this arrangement. Flux control that offers a high dynamic performance has been designed for induction motors in some applications, such as in electric traction. However, this is still a sophisticated and complex control system [14].

The hardware of most application controls has been simplified through the development of the machines with brushless permanent magnets. There are currently two types of machines with brushless permanent magnet, of which the most popular is the permanent magnet synchronous motor (PMSM), which is supplied with sinusoidal currents. The second type is the brushless DC (BLDC) motor which is supplied with quasi- square-wave currents. In these two designs, the rotor copper losses are eliminated, giving a high peak efficiency when compared to the conventional induction motor [15].

2.3.1 The development and operation strategy of the BLDC motor

The BLDC motor is a form of motor in which the magnetic field from the stator and the rotor twirls are equal in frequency (synchronous motor). The “slip” that is common with the induction motors is not experienced in the BLDC motors. The magnet rotor and wire -wound stator poles are permanently built in the BLDC motor [16].

2.3.1.1 Stator

The BLDC motor stator has a stacked steel laminations with windings which are maintained in the axially cut slots along the inner surface Figure 2.1. There are 3 stator windings in most BLDC motors which are interlinked in a star fashion and these windings are generated from various coils that are linked to derive a winding. Windings are formed from one or more interconnected coils and maintained in the slots; each winding is distributed over the stator periphery to form an even number of poles [16].

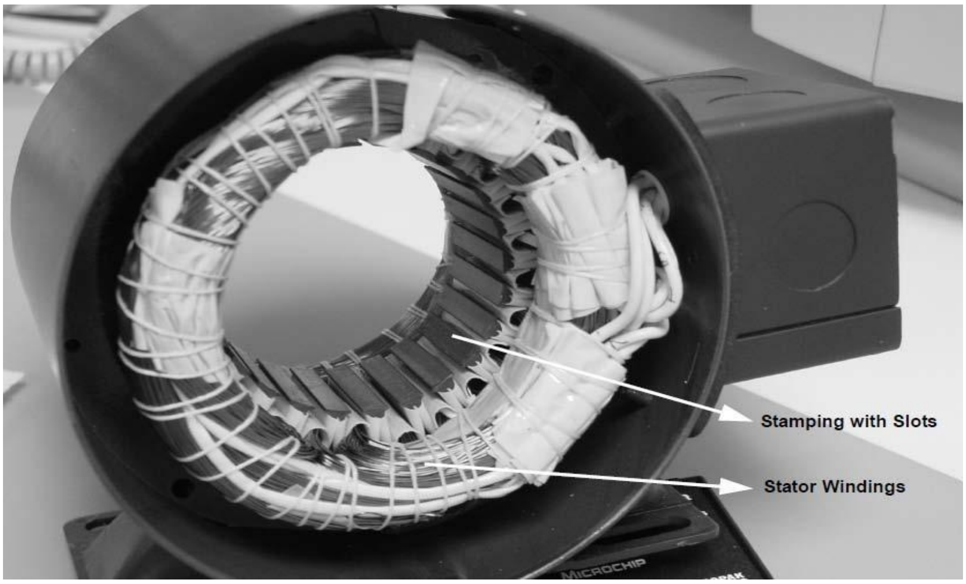
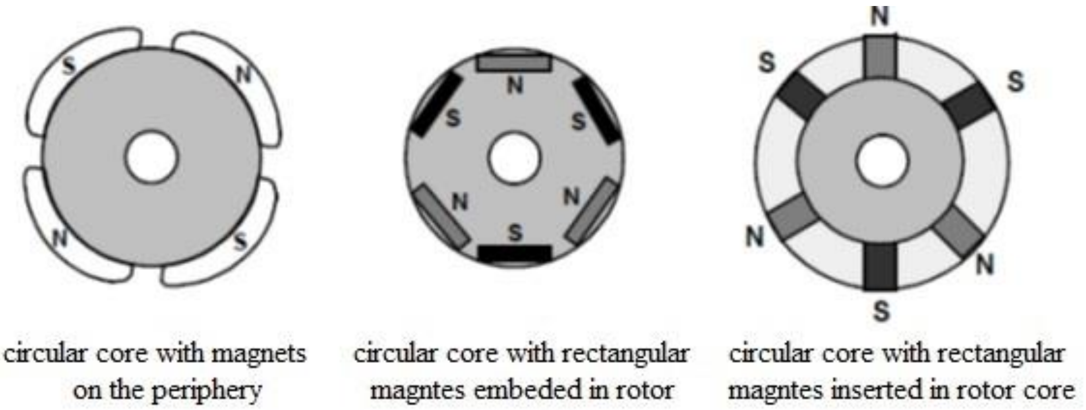


Figure 2.1: The stator of BLDC motor [16]

2.3.1.2 Rotor

Figure 2.2 shows rotor magnetic of a BLDC motor. Permanent magnets form the rotor of the BLDC and can be alternated between 2 and 8 pole pairs with alternate N and S poles. The field density of the rotor in a motor determines the suitable magnetic materials to be selected; the permanent magnets are made with ferrite magnets, but these days, rare earth alloy magnets are attracting attention [17].



circular core with magnets on the periphery

circular core with rectangular magntes embeded in rotor

circular core with rectangular magntes inserted in rotor core

Figure 2.2: Rotor magnet cross section [17]

2.3.1.3 Hall sensors

BLDC commutation is always checked electronically and the stator windings must be somewhat energized to rotate the BLDC motor. A knowledge of the rotor position is necessary to ascertain the winding to be energized. Hall effect sensors incorporated in the non-driving end of the motor stator helps in sensing the rotor position Figure 2.3; should the poles of the rotor magnetic move towards the sensors (Hall sensors), signals (high or low) which suggests the N or S pole passing near the sensors will be generated. The commutation order is determined from a combination of the 3 Hall sensor signals [18].

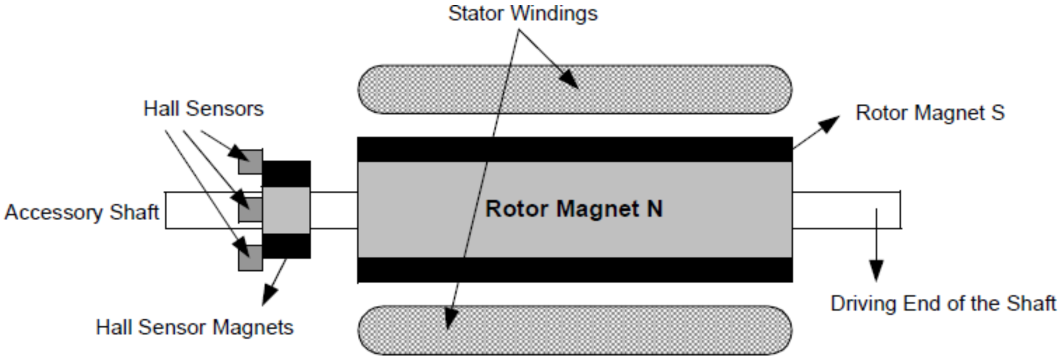


Figure 2.3: The rotor and Hall sensors of a BLDC motor [18]

2.3.1.4 The operation principle

One of the windings in each commutation sequence is positively energized, while the second winding is negatively energized and the third one has no charges. Torque is stimulated from the stator coil-magnetic field (from permanent magnets) interaction. Ideally, the torque usually peaks when the angle between these two magnetic fields is 90° and tends to decrease as the fields become closer to each other. To run the motor, there must be a shift in the position of the magnetic field generated by the windings when the rotor moves close to the stator field [19].

2.3.1.5 Commutation sequence

There is a change in the state of the Hall sensors in every 60^o of electrical rotation. An electrical cycle takes up to six steps to be completed. Additionally, there is a renovation of the phase current switching per every 60 electrical degrees Figure 2.4. However, an electrical cycle and one rotor mechanical revolution may not correspond as the rotor poles determine the number of electrical cycles to complete a rotor mechanical revolution. For each pair of rotor poles, an electrical cycle is completed; hence, the number of electrical cycles corresponds to the rotor pole pairs. The BLDC motor is balanced with a three-phase bridge inverter. The running of the motor requires the switching of 6 switches based on the Hall sensor inputs [16].

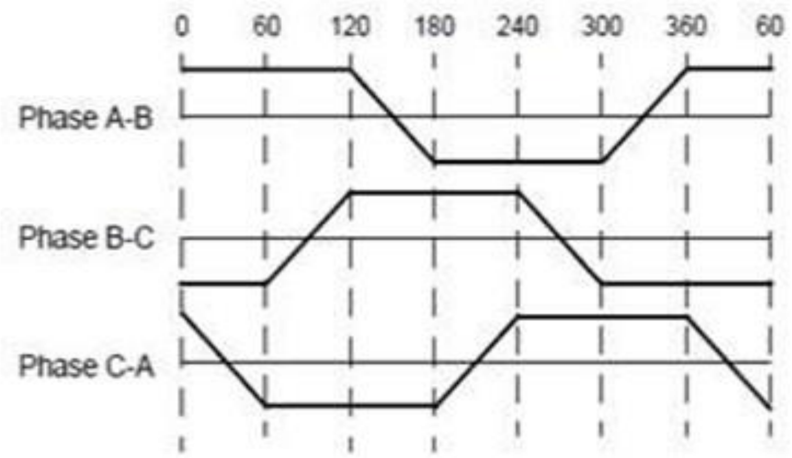


Figure 2.4: Trapezoidal back EMF [20]

The switches are turned ON or OFF using Pulse width modulation techniques. To alter the rotor speed, these signals must be at a pulse width modulated (PWM) frequency which must be 10 time higher than the motor frequency. The average voltage to the stator must be reduced if a difference exists in the PWM duty cycle within the sequences, and this will reduce the rotor speed. Similarly, another issue with the PWM is the regulation of motor by reducing the percentage of the PWM duty cycle of the corresponding motor rated voltage if the voltage of the DC bus is more than that of the motor rated voltage. This makes it possible to assemble motors with different voltages, and also through PWM duty cycle control, can meet the controller average voltage output to the motor voltage. The power of the magnetic field from the energized motor windings (a factor of the current passing through) determines the torque and speed of the motor. Hence, the motor speed can be regulated by adjusting the rotor voltage [16].

2.3.2 Torque/speed characteristics

The torque/speed characteristics is shown in Figure 2.5. Two torque parameters - peak torque (T_P), and rated torque (T_R) are needed to define a BLDC motor. The motor of a BLDC rotor can be loaded up to the rated torque during a continuous operation and the torque can remain constant for a speed range up to the rated speed [21].

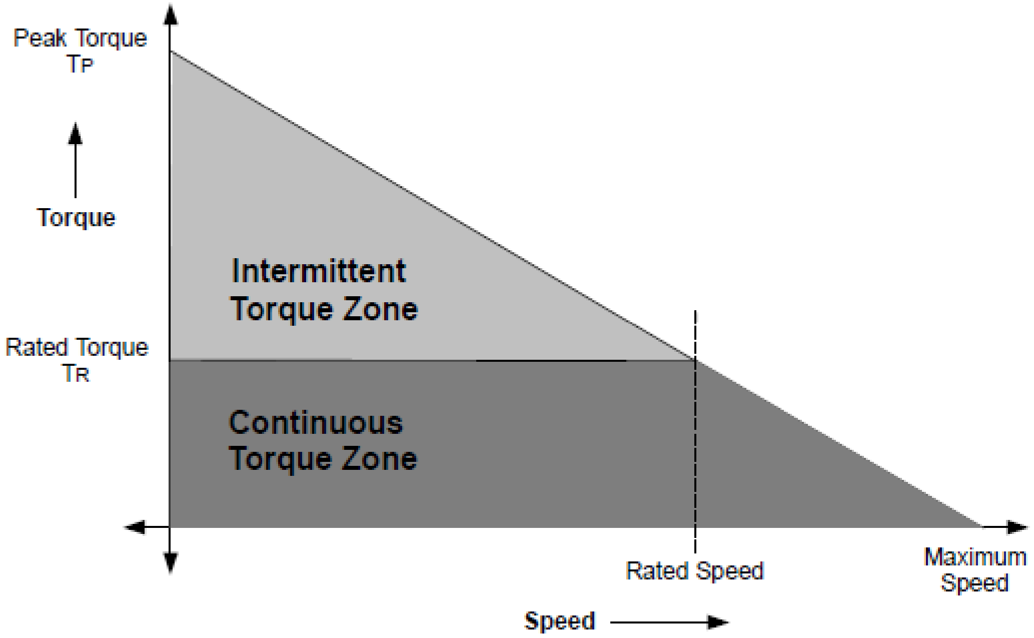


Figure 2.5: Torque-speed characteristic of a BLDC motor [22]

The motor can operate to up to 150 % of the rated speed before a drop in the torque can be noticed. Some applications with loads on the motor which experience frequent switching and reversal of rotation usually demands more than the rated torque. This is encountered over a brief period, especially during acceleration and during the starting of the motor from a standstill. Within this period, there is need for extra torque to overcome the load and rotor inertia. In as much as the speed-torque curve is followed, the motor can produce torque that is up to the peak torque. There is a less inertia in the BLDC motor compared to the other types of motor because the rotor is made of permanent magnets. This enhanced the acceleration and deceleration characteristics, and reduced the operating cycles. A predictable speed regulation is produced by their linear speed/torque characteristics [23].

2.3.3 Three Phase Inverter

Brushless DC motors use electric switches to realize current commutation, and thus continuously rotate the motor. These electric switches are usually connected in a three-phase bridge structure for a three-phase BLDC motor shown in Figure 2.6. Usually the high-side switches are controlled using pulse-width modulation (PWM), which converts a DC voltage into an AC voltage, which easily and efficiently limits the startup current, control speed and torque. Generally, raising the switching frequency increases PWM losses, though lowering the switching frequency limits the system's bandwidth and can raise the ripple current pulses to the points where they become destructive or shut down the BLDC motor driver.

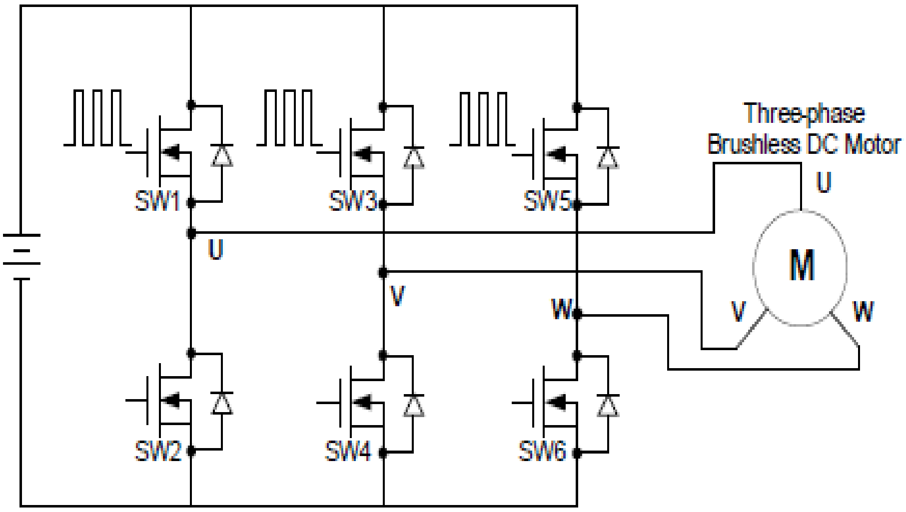


Figure 2.6: Three Phase Inverter

2.4 Control strategy

The issues of the open-loop controller curtailed through the introduction of the feedback closed-loop controller which controls the state and output of dynamical systems using feedback. The name is derived from the information path in the system. The input, such as the voltage supplied to an electric motor can influence the outputs (motor speed or torque) which the controller sense and control. The output (control signal) serve as the process input in closing the loop. The advantages of the closed-loop controllers over the open-loop controllers are as follows:

i. Rejects disturbances such as un-sensed friction within a motor.
ii. Ensures better performances even in the presence of model structural uncertainties.
iii. The model parameters are not exact, and does not perfectly match the real process.
iv. Can stabilize unstable processes.
v. Has a reduced sensitivity to parameter changes.
vi. Has an improved performance in tracking references.

The closed and open-loop controls are simultaneously used in some systems, where the open-loop control is regarded as the feedforward which works on the improvement of the reference tracking performance of the system [24].

2.4.1 Closed-loop transfer function

The system output y(t) is fed back to the reference value r(t) via a sensor measurement Z. The controller C_1 then, changes the input to the system under control C_2 by computing the reference-output error difference Figure 2.7. These are referred to as closed-loop or feedback controllers, also referred to as a single-input-single-output (SISO) control system, but when the input/output is more than one, it is known as a multi-input-multi-output (MIMO) system. The variables are designated as vectors in such cases rather than scalars. The vectors may be infinite dimensions in some distributed parameter systems [25]

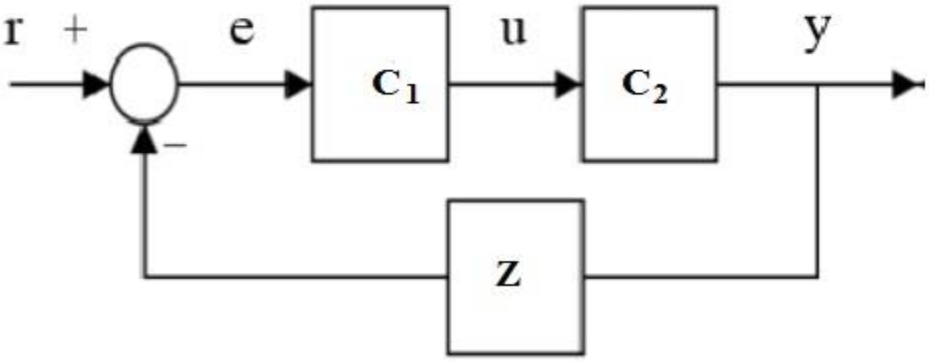


Figure 2.7: A closed-loop control system [25]

The controller (C_1), plant (C_2), and sensor (Z) from Figure 2.6 can be assumed to be linear and time-invariant, meaning that their transfer function elements C_1(s), C_2(s), and Z(s) is not time-dependent. The following relations can be generated by analyzing the above system Laplace variable transform:

$$Y(s) = C_2(s)U(s) \tag{2.1}$$
$$U(s) = C_1(s)E(s) \tag{2.2}$$
$$E(s) = R(s) - Z(s)Y(s) \tag{2.3}$$

Y(s) in terms of R(s) gives:

$$Y(s) = \left(\frac{C_2(s)C_1(s)}{1+Z(s)C_2(s)C_1(s)}\right)R(s) = H(s)R(s) \tag{2.4}$$

$$H(s) = \left(\frac{C_2(s)C_1(s)}{1+Z(s)H(s)}\right) \tag{2.5}$$

The expression above represents a system's closed-loop transfer function; the numerator set represents the open-loop gained from r to y, while the denominator set is the so-called loop gain (1 + gain from going around the feedback loop). If $|C_2(s)C_1(s)|$ >> 1, (i.e. each value of s having a large norm), and if $|Z(s)| \approx 1$, Y(s) and R(s) are then, approximately equal, which implies setting the output control reference [25].

2.5 Proportional Integral Derivative (PID) Controller

A PID controller is a generic feedback control loop system that is commonly used in several control systems at industrial scale. It is the commonest deployed feedback controller which determines error values by calculating the variation of a measured variable from the desired variable. The PID controller adjusts the process input in trying to reduce the process error level. The PID controllers are best utilized when the knowledge of the underlying process is lacking. To achieve an optimum PID performance, the parameters employed for the error calculation must be in tune with the system, while the design must be generic. The parameters are selected based on the system specifications. A block diagram of the PID controller is shown in Figure 2.8 [26].

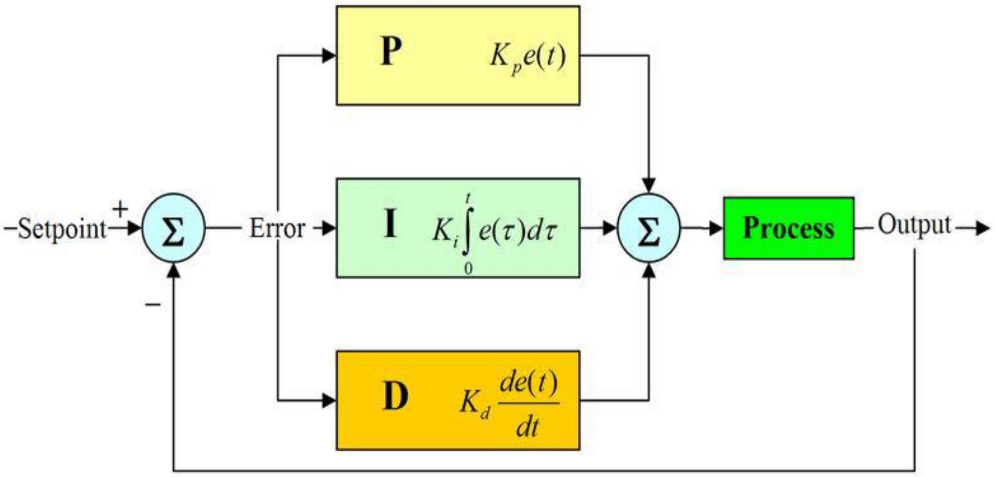


Figure 2.8: The schematic of a PID controller [27].

Calculations in the PID algorithm involves the use of the proportional, integral and derivative values (the component parameters of PID) denoted P, I, and D, respectively. These parameters are sometimes referred to as a three-term control. The reaction that occurs is determined by the proportional value while the integral value utilizes the recent errors to determine the reaction. The derivative value deploys the rate of error changes to determine the reaction. The process is adjusted using the weighted sum of these 3 actions through a control channel such as the power supply of a heating element or the position of a control valve. These variables can heuristically be represented in terms of time: ‘P’ is dependent on the current error; ‘I’ depends on the accumulated previous errors; ‘D’ utilizes the current rate f error to forecast the future error [28].

The controller can specifically control a process to the requirement by tuning the 3 components in the PID algorithm. The controller’s response can be in the form of the degree of setpoint overshooting by the controller, the responsiveness of the controller to an error, and the rate of system oscillation. It is worthy to note that using the PID controller does not ensure an optimal system stability. Some systems may need the use of 1 or 2 modes for an efficient control. This is achievable through setting the gain of undesired outputs to zero. Without the respective control actions, a PID controller can be referred to as either a PI, PD, P or I controller. The PI controllers are common due to the sensitivity of the derivative action to measurement noise; while the system may be prevented from attaining the target by the absence of an integral value as a result of control action. Further details on the PID control system is provided by [29].

The commonest feedback control mechanism is the PID controller. The PID refers to the 3 components that processes error signals to produce control signals. Let u(t) = the control signal received by the system, y(t) = the measured output, r(t) = the desired output, and tracking error e(t) = r(t) − y(t), the general form of a PID can be represented as:

$$u(t) = K_p e(t) + K_I e(t) + K_D \frac{d}{dt} e(t) \qquad (2.6)$$

The three parameters k_p k_i, and k_d can be adjusted to obtain the desired closed-loop dynamics often by iterative tuning and with no special knowledge of a plant model. The proportional term ensures system stability; while the integral term allows step disturbance rejection. The response can be shaped or damped using the derivative term. Among the control systems, the PID controllers stands out as the commonest and most established: however, they are not applicable in complex situations, especially when considering MIMO systems [28].

The Laplace transformation can be applied in the equation of PID controllers as follows:

$$U(s) = K_p e(s) + K_I \frac{1}{s} e(s) + K_D s e(s) \tag{2.7}$$

$$U(s) = \left(K_p + K_I \frac{1}{s} + K_D s\right) e(s) \tag{2.8}$$

with the PID controller transfer function:

$$C(s) = \left(K_p + K_I \frac{1}{s} + K_D s\right) \tag{2.9}$$

The 3 correcting terms whose sum give rise to the manipulated variable made up the name ‘PID control scheme’; therefore,

$$MV(t) = P_{out} + I_{out} + D_{out} \tag{2.10}$$

where P_{out}, I_{out}, and $D_{out}$are the contribution of three terms of the PID controller to the output, as defined below.

2.5.1 Proportional term

The proportional term effect changes proportional to the current error value on the output. A multiplication of the error with K_p (a constant known as the proportional gain) can adjust the proportional response [24].

The proportional term is denoted as:

$$P_{out} = K_p e(t) \tag{2.11}$$

where

P_{out}: the output’s proportional term

k_p: the tuning parameter

e: the error $= \mathrm{SP} - \mathrm{PV}$

t: the instantaneous time

A huge variation in the output of an error change can result from high proportional gain. With a very high proportional gain, the system may become unstable, but in the presence of a small gain, a small output response to a large input error may result, reduce the sensitivity of the controller. A too low proportional gain may result t a too small control action when responding to system noise. Without any form of disturbances, the pure proportional control won't settle at the target value, but will maintain a steady error state (droop) which is determined by the proportional and process gains. In specific terms, if the process gain of an error is represented as G and taken to be relatively constant, then, droop occurs when the proportional output term P_{out},and the constant gain are equal, which is linear in the error, G = k_pe, so e = G / k_p. Such is experienced pulling power (process gain that pulls the parameter away from the set point) is more than the pushing power (the proportional term that pushes the parameter close the set point). With a low process gain, the set point will be more than the steady state, hence, "droop" [25].

Regarding droop, the process gain drift component is only considered; random or regular fluctuations below or above the drift are eliminated. The process gain can change with time or in in response to external variations such as a faster or slower cooling when there are changes in the room temperature. Droop is directly related to the process gain but relates inversely to the proportional gain, and it is an unavoidable issue with pure proportional controls. The introduction of a bias term such as selecting a setpoint that is higher than the desired value can mitigate droop. Similarly, the addition of an integration term PID controller (which can effectively and adaptively compute bias) can correct droop. Irrespective of the droop, the proportional term has been shown by both tuning theory and industrial practice to contribute the bulk of the output change [25].

2.5.2 Integral term

The level of integral term effect which is often referred to as "reset" is related to the error duration and magnitude. A summation of the current error with time provides the cumulative offset that ought to have been previously corrected. The cumulative error is then, added to the controller output after multiplication with the integral gain.

The integral gain Ki determines the weight of the integral term's contribution to the control action [24].

The integral term is depicted as:

$$I_{out} = Ki\int_0^t e(\tau)\,d\tau \tag{2.12}$$

where

I_{out} : Integral term of output

K_i: Integral gain, a tuning parameter

e: Error = SP − PV

t: Time or instantaneous time (the present)

τ: a dummy integration variable

When proportional and integral terms are added, the migration of the process to the setpoint is enhanced and inherent steady-state error which are encountered when using only a proportional controller is removed. Meanwhile, as the integral term responds to the previous errors (accumulated), there could be an overshoot of the current value above the setpoint through crossing the setpoint and deviating in the other direction. Refer to the section on loop tuning for further insights on controller stability and integral gain tuning [24].

2.5.3 Derivative term

A determination of the slope of the error over time and its multiplication by the derivative gain K_d gives the rate of change of the process error. The level of the derivative term effect to the general control process is referred to as the derivative gain, K_d, which is given by:

$$D_{out} = K_d\frac{d}{dt}e(t) \tag{2.13}$$

where

D_{out}: Derivative term of output

K_d: Derivative gain, a tuning parameter

e: Error = SP – PV

t: instantaneous time.

The close noticeable derivative term reduces the level of controller output changes, and this mostly affects the setpoint of the controller. Therefore, the weight of the produced overshoot is reduced by the integral component using the derivative control; it also improves the combined stability of the controller process. Meanwhile, noise is amplified by a differentiation of a signal, and thus, this term in the controller has a high sensitivity to noise in the error term, and can make a process unstable if there is a large range of noise and derivative gain. Hence, there is usually an approximation to a differentiator with a few bandwidths, and such circuits are called phase-lead compensators [25]. The output of the PID controller is calculated by summing the proportional, integral, and derivative terms. When u(t) is the controller output, the PID algorithm has a final form as follows:

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau) d(\tau) + K_d \frac{d}{dt} \qquad (2.14)$$

where the tuning parameters are:

proportional gain, K_p

Faster responses are denoted by larger values since larger errors corresponds to larger proportional term compensation. Process instability and oscillation can result from an excessively large proportional gain.

Integral gain, K_i

Larger internal gain value implies a quicker rate of steady state error elimination. The trade-off is a larger overshoot, where negative errors integrated during the transient response must be back integrated by the positive error prior to reaching the steady state

Derivative gain, K_d

Larger derivative gain value reduces overshoot, but similarly decreases the transient response. It may also result in the system instability due to the amplification of the signal noise in the error differentiation [25].

2.5.4 Loop Tuning

Control loop tuning implies adjusting its control variables such as the proportional band, game band, derivative gain, derivative rate, and integral reset and integral gain to the maximum values to achieve a desired response. A basic requirement for tuning is stability but beyond it, different systems behave differently, have different requirements and some desiderata conflict. There is some aspect of nonlinearity in some processes and parameters may perform well when fully loaded, but never works starting up from a no-load situation. This can be resolved through using different parameters in different operating regions (gain scheduling) [30].

Even without tuning, PID controllers usually offer an acceptable level of control, but a careful tuning can improve the performance. A poor tuning can result to a poor performance even though there are only three parameters with simple principles. This is because complex criteria within the PID control limitations must be met. There are several tuning methods and more complicated methods have been patented. Some of the manual traditional methods of loop tuning are described in this section [30].

Several PID loop tuning methods are presented in Table 2.1. Some of the effective methods involve process model development, followed by the choosing of components (P, I, and D) based on the model’s dynamic variables. The manual methods are relatively not efficient when the loop response time is long. Selecting a method mainly depends on the mode of running the loop (offline or online) and on the response time of the system. systems that can be run offline can utilize methods which usually involves system subjection to a stepwise change in input, measuring output based on the time, and determining the control parameters using this response [31].

Table 2.1: The selection of a PID controller tuning method [31]

Method	Merits	Demerits
Manual Tuning	An online method that requires no calculation	Experienced personnel is needed.
Zeigler Nichols	A proven online method.	Requires some process upset; involves much trying; needs an extensive tuning.
Software Tools	Offers a consistent tuning in both online and offline platforms. May require sensor and valve analysis. Simulation can be performed before downloading	Requires some cost and training.
Cohen-Coon	Good process models	Requires some computations, mainly offline-based, and only ideal for first order processes.

The effects of independently increasing a parameter is shown in Table 2.2. To maintain online status of a system, the best way is to first zero the values of $\mathrm{K_i}$ and $\mathrm{K_d}$, and increase the value of $\mathrm{K_P}$ until loop output oscillation is observed. The value of K_P should be approximately half of the value for a "quarter amplitude decay" type response, then, increase $\mathrm{K_i}$ until any offset is correct in sufficient time for the process [31].

Table 2.2: The effects of independently increasing a parameter [32]

Parameters	Rise Time	Overshoots	Settling Time	Steady-State Error	Stability
$\mathrm{K_P}$	Decreased	Increased	Slightly changed	Decreased	Degraded
$\mathrm{K_i}$	Decreased	Increased	Increased	Decreased significantly	Degraded
$\mathrm{K_d}$	Slightly decreased	Slightly decreased	Slightly decreased	No effect in theory	Improved if K_d small

However, there will be much instability if the $\mathrm{K_i}$ is too much. Finally, increase $\mathrm{K_d}$, if necessary until the loop can reach its reference after a load disturbance at an acceptable rate. However, excessive response and overshoot can result from too much $\mathrm{K_d}$. A fast and efficient PID loop tuning quickly reaches its setpoint with a slight overshoot; however, overshoot may not be tolerated in some systems, in which case, there will be a need for closed-loop system (overdamped) that will need a significantly less K_P setting compared to half of the K_P setting that caused oscillation [31].

In Table 2.3, a tuning method (heuristic) which was originally referred to as Ziegler–Nichols method is presented.

Table 2.3: The Ziegler–Nichols heuristic tuning method [33]

Control Type	k_p	k_i	k_d
P	0.5 k_u	-	-
PI	0.45k_u	1.2 k_p /P_u	-
PID	0.60 k_u	2 k_p/P_u	$k_p P_u$/8

Similar to the above method, the k_i and k_d gains were first zeroed. The P gain was increased until the ultimate gain, K_u where the loop output began to oscillate was reached. The gains were set using the K_u and oscillation period P_u, as shown on Table 2.3 [33].

2.6 Fuzzy logic

The last few decades have witnessed the conversion of human intelligence via artificial means in a form understandable by computers. Intelligent control implies an advanced control that is based on AI techniques. The intelligent systems have often been compared to the biological systems by examining the way humans perform some tasks, make decisions and recognize patterns. A mismatch exists between machines and humans: humans think in an imprecise, uncertain, and fuzzy manner while machines deploy binary reasoning. Fuzzy logic is a way of enabling machines to reason in a fuzzy manner like humans become more intelligent. Fuzzy logic which was introduced in 1965 by Lotfy Zadeh presented as a tool for dealing with imprecise, uncertain, and qualitative decision-making issues. To control complex and dynamic systems, controllers that utilize a combination of intelligent and conventional techniques are usually deployed. Therefore, the embedded fuzzy controllers automate activities that are traditionally controlled by human [34].

In the traditional control approach, physical reality modeling is required. The system can be described using three methods: an input-output table can be characterized by determining the way processes react to different inputs. In a graphical form, the method can be represented as having the input of an input-output curve plotted on the x-axis while the output is plotted on the y-axis. Through an understanding of such reaction, a controller can be designed. There are several disadvantages though: the equipment for the process may be available, the cost of the procedure may be high, it may be difficult to measure the output in case of a large input values; interpolation between the required ad the measured outputs maybe needed. Care must be taken when determining the ranges of the expected inputs and outputs to ensure they are within the limit that can be measured by the available instruments [35].

In control engineering, there is a need for an idealized mathematical model for process control, mainly in the form of difference or differential equations. The widely used equations are Laplace transforms and z-transforms. To simplify the mathematical models, there are some assumptions, and one of the assumptions is the linearity of the process; it is assumed that the output and input are proportional to each other. Linear techniques are desired because they offer a better insight [35].

Additionally, there is no universal concept for the analysis of differential equations, and as a consequence, there is no comprehensive tools for the analysis of nonlinear dynamic systems. The second thing to assume is the stability of the process parameters with time despite the deterioration of the system components as well as environmental changes [36].

In developing a realistic and meaningful mathematical description of an industrial process, the following issues are encountered:

i. A poor understanding of the phenomena
ii. An inaccurate value of various parameters
iii. The complexity of the model

Heuristic methods comprise of modeling and understanding based on past experiences, rules-of-thumb, and frequently-used strategies. A heuristic rule is logically in the form: ‘IF’ <condition> ‘THEN’ <consequence>, or in a typical control situation: If <condition> Then <action>. Rules reconcile conditions with conclusions. The heuristic method is the same as the experimental construction of a table of inputs and their respective output values, rather than having crisp numeric

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