

**COMPARATIVE STUDY BETWEEN PID CONTROLLER AND FUZZYPID
CONTROLLER FOR SPEED CONTROL OF PM BLDC MOTOR DRIVE**

by

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UNIVERSITI SAINS MALAYSIA

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LIST OF SYMBOLS

K_p, K_i, K_d	proportional, integral and derivative gain
F_{Kp}, F_{Ki}, F_{Kd}	fuzzyPID gain
V_{an}, V_{bn}, V_{cn}	phase voltages
V_{a0}, V_{b0}, V_{c0}	phase voltages referred to neutral
i_a, i_b, i_c	phase currents
ψ_a, ψ_b, ψ_c	phase flux linkages
R_s	phase winding resistance
L	self-inductance
M	mutual inductance
e_a, e_b, e_c	phase back-EMF
L_a, L_b, L_c, L	phase inductance
R_a, R_b, R_c, R	phase resistances
$L_{ab}, L_{ba}, L_{ac},$ L_{ca}, L_{bc}, L_{cb}	mutual inductance between phases
k_T	torque constant
k_e	EMF constant
ω_r	rotor speed
T_e	electromechanical torque
T_l	load torque
P_e	electrical power
P_m	mechanical power
θ_r	electrical rotor position angle

p	number of poles
B	frictional coefficient
J	moment of inertia
h	hysteresis band
f	frequency of the system

LIST OF ABBREVIATIONS

BLDC	Brushless DC
PID	Proportional Integral Derivative
COA	Centroid of Area
MOM	Mean of Maximum
FLC	Fuzzy Logic Control
PM	Permanent Magnet
Back EMF	Back electromotive force
MOSFET	Metal Oxide Field Effect Transistor
DC	Direct Current
AC	Alternating Current
IGBT	Integral Gate Bipolar Transistor
PWM	Pulse Width Modulation
DSP	Digital Signal Processor
UL	Upper Level
LL	Lower Level
RPM	Rotation per Minute
GUI	Graphical User Interface
ANN	Artificial Neural Network
GA	Genetic Algorithm
MCPWM	Motor Control Pulse Width Modulation
NM	Negative Medium

NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PC	Personal Computer
ICD2	In-Circuit Debugger 2
HVAC	Heating, Ventilating and Air-Conditioning

KAJIAN PERBANDINGAN DI ANTARA PENGAWAL PID DAN PENGAWAL FUZZYPID UNTUK KAWALAN KELAJUAN MOTOR MAGNET KEKAL ARUS TERUS TANPA BERUS

ABSTRAK

Penyelidikan ini memberi tumpuan kepada kajian perbandingan di antara pengawal PID dan pengawal FuzzyPID untuk kawalan kelajuan motor magnet kekal arus terus tanpa berus (PM BLDC). Motor PM BLDC adalah lebih popular berbanding dengan motor elektrik yang lain yang menjadikannya digunakan secara meluas dalam banyak aplikasi. Adalah diketahui umum bahawa kebanyakan aplikasi di industri menggunakan pengawal PID konvensional. Kini, pengawal PID dianggap sebagai satu sistem konvensional di sebabkan oleh kewujudan beberapa kawalan pintar seperti Kawalan Logik Kabur (FLC). Walau bagaimanapun, pengawal PID masih lagi sesuai digunakan untuk melaksanakan satu sistem kawalan suapbalik. Apabila sistem tidak lurus menjadi isu utama dalam kawalan motor, ia adalah lebih baik untuk meningkatkan strategi kawalan PID dan bukannya membina model dinamik yang rumit yang memerlukan strategi kawalan yang canggih. Oleh itu, pengawal PID kabur (FuzzyPID) telah dicadangkan dan dibincangkan untuk kawalan kelajuan motor PM BLDC. Tindak balas kelajuan motor dikaji berdasarkan pelbagai keadaan operasi termasuk tindak balas terhadap perubahan kelajuan rujukan yang besar dan kecil beserta tindak balas terhadap kesan beban. Keputusan simulasi disokong dengan satu set keputusan eksperimen yang diperolehi dengan menggunakan pengawal PID dan FuzzyPID. Keputusan ujikaji menunjukkan bahawa pengawal FuzzyPID menghasilkan tindak balas kelajuan yang unggul iaitu hampir 0.1 s lebih pantas terhadap masa naik dan masa selesai beserta berjaya mengurangkan jumlah terlajak sehingga 20% berbanding dengan pengawal PID.

COMPARATIVE STUDY BETWEEN PID CONTROLLER AND FUZZYPID CONTROLLER FOR SPEED CONTROL OF PM BLDC MOTOR DRIVE

ABSTRACT

This research focuses on a comparative study between PID controller and FuzzyPID controller for speed control of permanent magnet brushless (PM BLDC) motor drive. PM BLDC motors are more popular over the other types of electric motors which make PM BLDC motors widely used in many applications. It is well known that most of the industrial applications used conventional PID controllers. Nowadays, PID controller is considered as a conventional system due to the existence of several intelligent controls such as Fuzzy Logic Control (FLC). However, PID controller still remains a valid approach to implementing a feedback control system. When the nonlinearities of the system are the major issues in motor control, it could be more convenient to improve the PID control strategy rather than to work out complicated dynamic models which require sophisticated control strategies. Thus, FuzzyPID controller has been proposed and discussed for speed control of PM BLDC motor. Motor speed responses are studied under different operating conditions including response to small and large step speed reference change, and response to step load application. Simulation results are supplemented with a set of experimental results, obtained using PID and FuzzyPID controllers respectively. The experimental results showed that FuzzyPID controller provides a superior speed response with approximately 0.1 s faster of the rise time and settling time as well as managed to reduce the amount of overshoot until 20% compared to the PID controller.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter will present a general overview of the speed control for Brushless DC (BLDC) motor, along with some explanations on what, why and how this research has been conducted. In Section 1.1, the background of the electrical machines is presented. Section 1.2 briefly describes the speed controller for the BLDC motor. Problem statement in Section 1.3 is discussed on why this research should be conducted, while Section 1.4 provides the research objectives. The outlines and structure of the thesis are given in the end of this chapter.

1.2 Background of study

Electric motors have broad applications in such areas as industry, household electrical appliances, machine tools and others. In industrially developed nations and large developing nations, it can clearly be seen that electric motors account for a considerable proportion of total national power consumption. Statistics indicate that electric motors are generally responsible for about 2/3 of industrial power consumption in each nation, or about 40% of overall power consumption (APEC, 2008).

Three phase BLDC motors play vital role in many of today's applications ranging from industrial, medical, aerospace, consumer, automotive and so forth. BLDC motor has several advantages, among which it has an excellent speed versus torque ratio, high efficiency, long operating life, noiseless operation and relatively small size with high torque (Yedamale, 2003). All these characteristics make BLDC motor an excellent

choice over brushed DC motor and induction motor for those applications which have been mentioned above.

1.3 Speed controller of BLDC motor

In BLDC motor drive application, the outer speed loop provides the reference value of current for the inner current loop and any disturbance in the speed controller output would affect the reference current, thus degrading the system performance. Hence, proper operation of the speed controller is of great importance for the drive performance (Amit et al., 2011)

A standard approach for speed control in industrial drives is to use a proportional plus integral plus derivative (PID) controller because of their simple control structure, ease of design and effectiveness for linear systems. However, most of the real systems are nonlinear or without of precise mathematical model. Due to their linear structure, conventional PID controllers are usually not effective for this kind of real systems. If advance control strategies are used instead, the system will perform more accurately or robustly. Therefore, it is often desirable to develop a controller that has the ability to adjust its own parameters according to the situation in which it works in order to yield satisfactory control performance (Ahmed et al., 2001).

Recent developments in artificial-intelligence-based control have brought into focus a possibility of integrating a Fuzzy Logic Control (FLC) with a PID speed controller. In the last decade, FLC has attracted considerable attention as a tool for novel control approach because of the variety of advantages that it offers over the classical control techniques.

The FLC has been an active research topic in automation and control theory since the work of Mamdani proposed in 1974 based on the fuzzy sets theory which was done by Lotfi Zadeh in 1965 to deal with the system control problems which are not easy to be modeled. The concept of FLC is to utilize the qualitative knowledge of a system to design a practical controller (Abdel et al., 2007). Unlike other conventional control schemes, FLC is a model free controller. It does not require an exact mathematical model of the controlled system and therefore, it is less sensitive to system parameter changes.

The variety of application and easiness to implementing the FLC tends to spread out the study in this area. Recently, FLC has been used especially on decision making, optimization and classification areas. In the field of electrical machines and drives, Japan has lead to ever expanding research activities and further the applications to all over the world. As early in 1985, the Sendai Subway control system has incorporated a fuzzy logic application into their subway system which was designed by Hitachi. The resulting system not only was simpler, but it has resulted in significant improvements in the degree of comfort and safety and has yielded cost savings. Since July 15, 1987 the nearly fully automated intelligent subway system carry passengers between stations with reputedly the highest degree of comfort and safety in the world – “straphangers don’t need to grip hard because the train stops are gentle as a kitten” (Soumitra, 1993). Although FLC was invented about 40 years ago, it has not lost its value yet. Each year thousands of studies are carried out on this field over the world.

1.4 Problem Statement

PID controllers are the well-known approach for the speed control of electrical machine drives because these control algorithms are simple, easy to implement and have small steady state error. However, these fixed-gain controllers do not give satisfactory response when there are parameter variations or load disturbances.

Nowadays, as a technology grows up, recent development in intelligent control system has emphasized the possibility to integrate the conventional PID controller with an intelligent controller such as FLC. However, PID controller remains a very valid approach to implementing a feedback control system. When the nonlinearities of the system are the major issues in motor control, it could be more convenient to improve the PID control strategy rather than to work out complicated dynamic models which require sophisticated control strategies. One of the factors that contribute to the nonlinearity of BLDC motor is the effects of magnetic saturation as well as reluctance variations. PID parameters need to be tuned based on the system environment. Thus, implementation of FuzzyPID controllers is also less complicated than the implementation of optimization algorithms of PID controller. Regardless of all the existing work, it appears that a detailed comparative analysis of the speed performance under PID and FuzzyPID controller, based on simulation and experiment, has not been done so far. The goal of this research is to provide such a comparison for a variety of operating conditions.

1.5 Research objectives

The main objective of this research is to evaluate and compare the performance of FuzzyPID controller with the conventional PID controller for speed control of three-

phase BLDC motor drive. Several objectives are defined specifically according to its priority:

- i. to develop knowledge based rules, fuzzy inference and membership functions for FuzzyPID closed-loop speed controller in simulation study and experimental work.
- ii. to build and simulate a PID closed-loop speed controller and a FuzzyPID closed-loop speed controller respectively in Matlab/Simulink.
- iii. to conduct experiments for 3-phase BLDC motor drive using PID closed-loop speed controller and FuzzyPID closed-loop speed controller respectively.
- iv. to compare and evaluate the performance of FuzzyPID closed-loop speed controller with that of PID closed-loop speed controller.

1.6 Structure of the thesis

This thesis is presented in six chapters. The introduction, as the first chapter covers the background information of the electrical machines drives and speed controller of BLDC motor. Problem statement and research objectives are also discussed. It is ended with the structure of the thesis.

Chapter 2 discusses the literature review regarding the 3-phase brushless DC motor which includes its construction, operating principles, and control technique. Mathematical model of BLDC motor also presented in this chapter. This chapter highlights the PID and FuzzyPID control as a close loop controller for speed control of BLDC motor. The Fuzzy Logic Control (FLC) algorithm also has been discussed. Then,

this chapter is ended with the discussions on recent research activities about FuzzyPID controller.

Chapter 3 focuses on the methodology employed in this research which consists of the design and development aspects of the simulation. The MATLAB/Simulink software has been used as the platform of the simulation analysis. The design flowchart is included to assist the understanding of the overall design and implementation processes that had taken place.

Chapter 4 presents the hardware implementation as well as the parameters used in the experimental setup. The source code development of PID and FuzzyPID controllers is discussed and shown with the aid of flow charts and the algorithm sequence.

Chapter 5 presents the results and analysis of the simulation and experimental study. The FuzzyPID controller performance is evaluated by comparing with PID controller for speed control of BLDC motor. Some graphs, figures and tables are shown and discussed as well.

Chapter 6 details out the conclusions and future works. The overall research findings are put together. Some summary on the system performance is also included. This chapter also describes about improvements that could be made and possible aspects that could be revisited.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter described the literature review which based on the four main scopes. It is begun with an overview of brushless DC (BLDC) motor and mathematical model of BLDC motor. Then it is followed by the description of speed control of BLDC motor as well as PID and FuzzyPID control systems. The end of this chapter was briefly discussed about Fuzzy Logic Control (FLC) system.

2.2 Introduction

The development of motor speed controller has always been increasing in terms of number as well as the level of complexity. The technological advancement in the capability of modern microcontrollers, power electronics converters and state of the art motor design, raises the demand for more comprehensive solutions for better control and efficiency. Electric motors have broad applications in such areas as industry, transportation, medical and household electrical appliances, powering a variety of equipment including wind blowers, water pump, compressors and machine tools. Among all the electric motors, the permanent magnet BLDC motors are very popular because of their high efficiency, high power factor, silent operation, compact form, reliability and low maintenance which make these types of motors are widely used in many applications. Apart from that, a standard approach for speed control in industrial drives is to use a PID controller. Nevertheless, PID controller has some weakness in controlling the nonlinear system. Hence, recent developments in technology have brought into focus a possibility of shifting from the conventional PID controller to the

artificial intelligent controller such as FLC. However, PID controller remains a valid approach to implementing a feedback control system. When the nonlinearities of the system are the major issues in motor control, there is an option to improve the PID control strategy rather than to replace with complicated dynamic models which require sophisticated control strategies. Thus, FuzzyPID controller can be one of the alternative solutions for improving the speed control of BLDC motor.

2.3 PM Brushless DC Motor

Due to historical, technical and economical aspect, brushed dc motor is the favorable choice in various applications. Brushed dc motors were commercialized in 1886 (Chapman, 2001). At the beginning of the 19th century, the permanent magnet (PM) excitation in electrical machine has been used for the first time replacing the electromagnetic excitation, but was not acceptable due to poor quality of PM materials. However the invention of Alnico in 1932, and later neodymium magnet (NdFeB) in 1985, revived the use of PM excitation system (Hendershot and Miller, 1994). The use of permanent magnet in electrical machine in place of electromagnetic excitation results in many advantages such as no excitation losses, simplified construction, improved efficiency, fast dynamic performance and high torque or power per unit volume (Kenjo and Nagamori, 1985).

In the 20th century, squirrel cage induction has become the most popular electric motors due to its rugged construction. Advancement in power electronics and digital signal processor has been adding more features to these motor drives to make them more widespread in industry. However in its operation scheme, induction motors require induction of magnetic field in the rotor by the rotating field of the stator resulting in the

electric and magnetic fields being out of phase. Therefore the squirrel cage induction motors have poor power factor and low efficiency as compared to the synchronous motor. These problems have led to the development of permanent magnet brushless dc motor, having permanent magnets on the rotor, replacing the mechanical commutator and brushes. The commutation is achieved by electronic switches, which supply current to the motor windings in synchronization with rotor position (Chapman, 2002; Hendershot and Miller, 1994; Kenjo and Nagamori, 1985 and Miller, 1989).

Permanent magnet brushless DC motors (BLDC) can be classified into two categories which is sinusoidal type and trapezoidal type. The first category uses continuous rotor position feedback for supplying sinusoidal voltages and currents to the motor. The ideal motional of back electromotive force (EMF) is sinusoidal, so that the interaction with sinusoidal currents produces constant torque with very low torque ripple. The torque ripple of BLDC motor is mainly influenced by the electronically commutation and form of back EMF (Hong et al., 2007). The sinusoidal motor needs a high resolution position sensor because the rotor position must be known at every time instant for optimal operation and this leads to the complexity of hardware and software design (Kim et al., 2007 and Sen, 1997).

The second category is called trapezoidal BLDC drive or rectangular fed drive. It is supplied by three-phase rectangular current blocks of 120° duration, in which the ideal motional back EMF is trapezoidal, with the constant part of the waveform timed correspond with the intervals of constant phase current. These machine need rotor position information only at the commutation points every 60° electrical in three-phase motors (Singh et al., 2006).

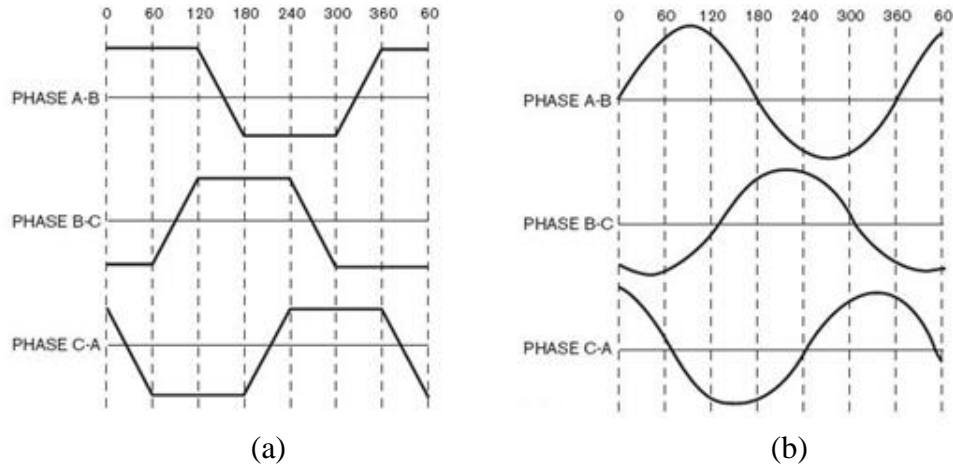


Figure 2.1: (a) Trapezoidal back EMF, (b) Sinusoidal back EMF (Yedamale, 2003)

Figure 2.1 shows the shape of trapezoidal and sinusoidal back EMF. According to (Afei et al., 2007 and Yedamale, 2003) the shape of back EMF is determined by the shape or the orientation of the rotor magnets and the stator winding distribution. Among the two types of BLDC motors, sinusoidal BLDC is developed for applications in which the accuracy is desired such as robotics, numerical controlled machines, solar tracking and others. However, the trapezoidal BLDC can be used in general and low cost applications. This motor is preferred for various applications because of their characteristics of high efficiency, silent operation, compact in size and low maintenance. Hence, scope of this thesis discusses the trapezoidal BLDC motors only. Figure 2.2 illustrated the cross section of side and front view of a typical brushless DC motor.

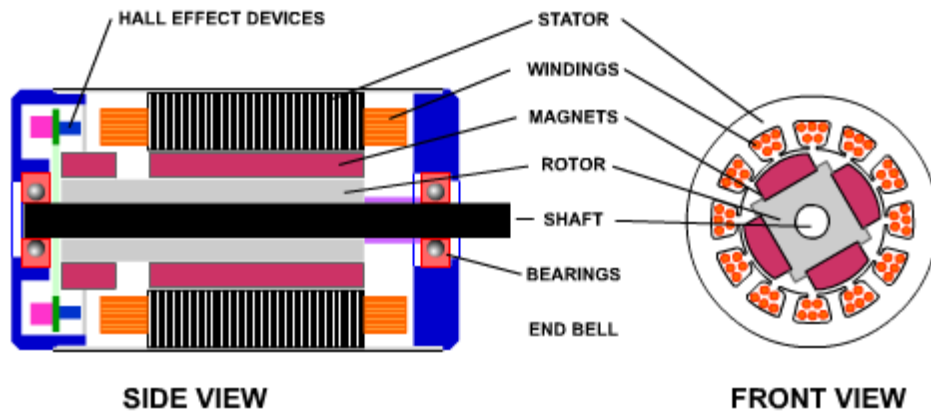


Figure 2.2: Cross section of BLDC motor (Brown, 2009)

The stator of a BLDC motor usually has three phase concentrated winding in either delta connection or star connection (wye connection). The ungrounded star-type connection is the most famous for brushless DC motor. Windings are made up of a number of interconnected coils, carefully placed in the slots that are made up of stacked steel laminations. Each of these windings is distributed over the stator slot to form an even number of poles and the most important thing is how the interconnection of the coil will determine the shape of back EMF waveform either sinusoidal or trapezoidal (Yedamale, 2003).

However the rotor constructions are varying according to the desired performances. (Singh et al., 2006) reported in the literature that there are variety of geometries of PM motors for better power density and efficiency by raising flux enhancement, reducing the armature reaction and high speed operation. Two main configurations of PM rotors are surface mounted magnet type where magnets are mounted on the outer surface of the rotor and the embedded magnet type where the

magnets are installed inside the magnetic structure of the rotor as shown in Figure 2.3.

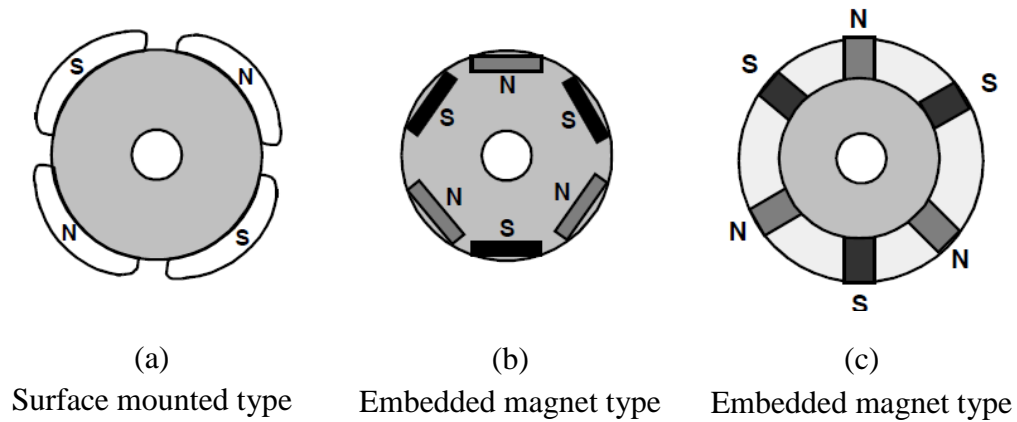


Figure 2.3 Rotor permanent magnets cross sections (Singh, 1997)

Another type of BLDC motor is the axial field machine where the direction of the magnetic field is axial instead of radial. The configurations of axial field BLDC motor include a single stator and single rotor, a single stator sandwiched between two rotors (double air gap), a single rotor sandwiched between two stators (double air gaps) and a variety of multiple stators and rotors (multiple air gaps) (Singh et al., 2006).

Another parts built in BLDC motor is rotor position sensors which can be using Hall sensor, resolvers or optical encoders. Hall sensors are used to determine the precise rotor position and so that the winding can be energized in right sequence. Hall sensors are embedded inside the stator at the non-driving end of the motor, normally separated from each other by either 60° (degree) or 120° (degree) depending on the manufacturer. Each time magnetic pole passes the sensors, all three sensors will produce a high (logic 1) or low (logic 0) signals to indicate the North or South pole. Each of the three Hall sensors will be at logical "1" for 180° (electrical degree) and will be at logical "0" for the remaining 180° (electrical degree).

Nowadays, it is also possible to run the BLDC motor without using the rotor position sensor, hence it is known as sensorless control. The basic idea of sensorless control method is to eliminate the use of position sensors. To accomplish this task, additional circuitry and complex algorithm are required to estimate the commutation instances of the BLDC motors from the voltage and current signals which can easily be sensed. Therefore, sensorless control methods demand high performance processors with large memory and program codes for computation and estimation, as compared to sensor based drive systems. That's why the sensed type is still a preferred choice for BLDC operation due to its ease of control.

2.4 Mathematical Model of BLDC Motor

BLDC motor can be modeled in the 3-phase abc variables which consist of two parts. The first is an electrical part which calculates electromagnetic torque and currents of the motor. The other is a mechanical part, which generates revolution of the motor. Referring to Figure 2.4, the electrical part of BLDC motor can be represented in matrix form as follows:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.1)$$

where V_{an} , V_{bn} and V_{cn} are the phase winding voltages, R_s is the resistance per phase for the stator winding, e_a , e_b and e_c are the phase back-emfs, while i_a , i_b and i_c are the phase currents.

If there is no change in rotor reluctance with angle because of a non-salient rotor being used, and assuming three symmetric phases, the following self- and mutual-inductances are obtained:

$$L_a = L_b = L_c = L \quad (2.2)$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \quad (2.3)$$

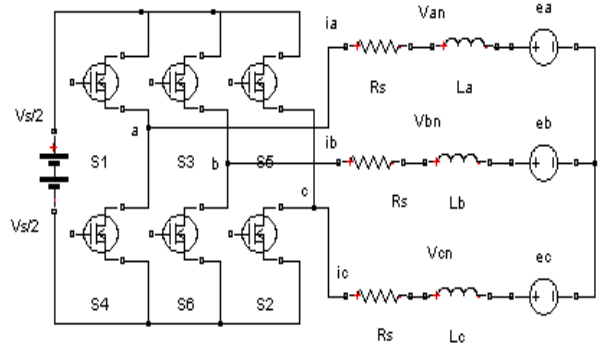


Figure 2.4: Equivalent circuit of BLDC Motor (I. Boldea and S. A. Nasar, 1998)

Substituting equations (2.2) and (2.3) in equation (2.1) gives the PM BLDC model as:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ L & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.4)$$

From equation (2.4), phase voltage for phase A, V_{an} can be derived as:

$$V_{an} = R_s i_a + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \quad (2.5)$$

$$V_{an} = R_s i_a + L \frac{di_a}{dt} + M \frac{d}{dt} (i_b + i_c) + e_a \quad (2.6)$$

The stator phase currents are constrained to be balanced such that $i_a + i_b + i_c = 0$. So equation (2.6) can be expressed as:

$$V_{an} = R_s i_a + (L - M) \frac{di_a}{dt} + e_a \quad (2.7)$$

Similarly for phase b and c:

$$V_{bn} = R_s i_b + (L - M) \frac{di_b}{dt} + e_b \quad (2.8)$$

$$V_{cn} = R_s i_c + (L - M) \frac{di_c}{dt} + e_c \quad (2.9)$$

where:

e_a is the phase-to-neutral back-EMF of phase A in volts,

e_b is the phase-to-neutral back-EMF of phase B in volts,

e_c is the phase-to-neutral back-EMF of phase C in volts,

i_a is the stator current in phase A in ampere,

i_b is the stator current in phase B in ampere,

i_c is the stator current in phase C in ampere.

Since the back-EMF waveforms are periodic, they can be represented by a periodic function. The voltage equation (2.7) of a BLDC motor can be depicted in the time domain by substituting as shown below:

$$v(t) = r_a i_a(t) + k_e \omega_r(t) + L_a \frac{di_a(t)}{dt} \quad (2.10)$$

where:

$v(t)$ is the supply voltage (line-to-neutral) in volts,

i_a is the armature current in ampere,

L_a is the armature inductance; $L_a = L - M$

$k_e \omega_r(t)$ is the line-to-neutral back-EMF, shown as E,

k_e is the back-EMF constant in Vs/rad.

ω_r is rotor angular velocity in mechanical radian/sec.

The Laplace form of equation (2.10) is given as:

$$I_a(s) = \frac{V(s) - k_e \omega_r}{r_a + sL_a} \quad (2.11)$$

By using the following equations, the transient model of a BLDC motor can be obtained as illustrated in Figure 2.4. If the current term is put aside in equation (2.10), we obtain:

$$\frac{di_a(t)}{dt} = \frac{v(t)}{L_a} - \frac{r_a}{L_a} i_a(t) - \frac{E(t)}{L_a} \quad (2.12)$$

where $E(t) = k_e \omega_r$ is the periodic back-EMF which is a function of the rotor angle.

Next, add equation (2.7), (2.8) and (2.9). So we get:

$$V_{an} + V_{bn} + V_{cn} = R_s(i_a + i_b + i_c) + (L - M) \frac{d}{dt}(i_a + i_b + i_c) + e_a + e_b + e_c \quad (2.13)$$

As shown in Figure 2.4, neutral voltages are referred to the zero reference potential at midpoint of dc-link. So the phase voltages can be expressed as:

$$V_{an} = V_{a0} - V_{n0} \quad (2.14)$$

$$V_{bn} = V_{b0} - V_{n0} \quad (2.15)$$

$$V_{cn} = V_{c0} - V_{n0} \quad (2.16)$$

where V_{a0} , V_{b0} , V_{c0} and V_{n0} are the output phase voltage from an inverter and the potential of the star point referred to the neutral. In order to avoid unbalance in applied voltages, a balance three phase winding star-connected is considered. This leads to obtain the value of V_{n0} by substituting equations (2.14), (2.15) and (2.16) into equation (2.13) and considering the equivalent of phase currents, equation (2.13) becomes:

$$V_{a0} + V_{b0} + V_{c0} - 3V_{n0} = (e_a + e_b + e_c) \quad (2.17)$$

Thus,

$$V_{n0} = \frac{V_{a0} + V_{b0} + V_{c0} - (e_a + e_b + e_c)}{3} \quad (2.18)$$

The developed electromagnetic torque can be expressed as:

$$T_e = \frac{(e_{an}i_a + e_{bn}i_b + e_{cn}i_c)}{\omega_r} \quad (2.19)$$

The relation between the electrical power, P_e , and the mechanical power, P_m , is:

$$P_e = E i_a = P_m = T_e \omega_r \quad (2.20)$$

The electromechanical torque, T_e , is linearly proportional to the armature current, i_a :

$$T_e = k_T i_a \quad (2.21)$$

where k_T is the torque constant. Equation (2.20) can then be substituted into equation (2.21) yielding equation (2.22).

$$T_e = \frac{E}{\omega_r} i_a \quad (2.22)$$

Such that for the ideal motor with no saturation, resistance, or voltage-drops in the controller, k_T becomes:

$$k_T = \frac{E}{\omega_r} = \frac{k_e \omega_r}{\omega_r} \approx k_e \quad (2.23)$$

Provided that k_T and k_e are in consistent units (such as Nm/A and Vs/rad).

The mechanical part of BLDC motor can be modeled as:

$$J \frac{d\omega_r}{dt} + B\omega_r = (T_e - T_l) \quad (2.24)$$

where J is moment of inertia in kg-m², B is frictional coefficient in N-ms/rad, T_l is load torque in Nm. The derivative of electrical rotor position θ_r , is expressed as:

$$\frac{d\theta_r}{dt} = \frac{P}{2} \omega_r \quad (2.25)$$

where P is number of poles, ω_r is the rotor speed in mechanical rad/sec and θ_r is the electrical rotor position in electrical radian.

2.5 PM BLDC Control Systems

The three-phase BLDC motor is operated in two-phase-on fashion. The voltage strokes need to be applied at the two phases out of three phases winding system at any instant of time, while the third phase is left open. The fact that two phases are energized at any instant of time provides high efficiency to the BLDC motor, mainly because the current density is much higher compared to energizing a single phase only. The maximum torque is delivered by BLDC motor when the stator flux and rotor flux is perpendicular to each other or at 90° angle. Based on the sequence, rectangular voltage strokes are applied to the respective stator windings and create flux. The stator flux then interacts with rotor flux that is generated by the rotor permanent magnet and thus producing rotational torque and speed.

The selection of which the two phases are energized depends on the rotor position. The energizing of the stator windings must be done according to a correct sequence via electronic commutation. The determination of the correct energizing sequence is achieved by translating the input from three Hall sensors that produced a three digit number that changed every 60° electrical degree as shown in Figure 2.5. For these three position sensors, each of the sensor will sense the rotor magnetic poles and produce whether a high (logic 1) or low (logic 0) signals to indicate North (N) or South (S) pole position. The important aspect is that the controller must be able to interpret the Hall sensor inputs and energize the stator windings respectively. Figure 2.5 illustrates the relationships between Hall sensor outputs and phase voltage energizing sequence.

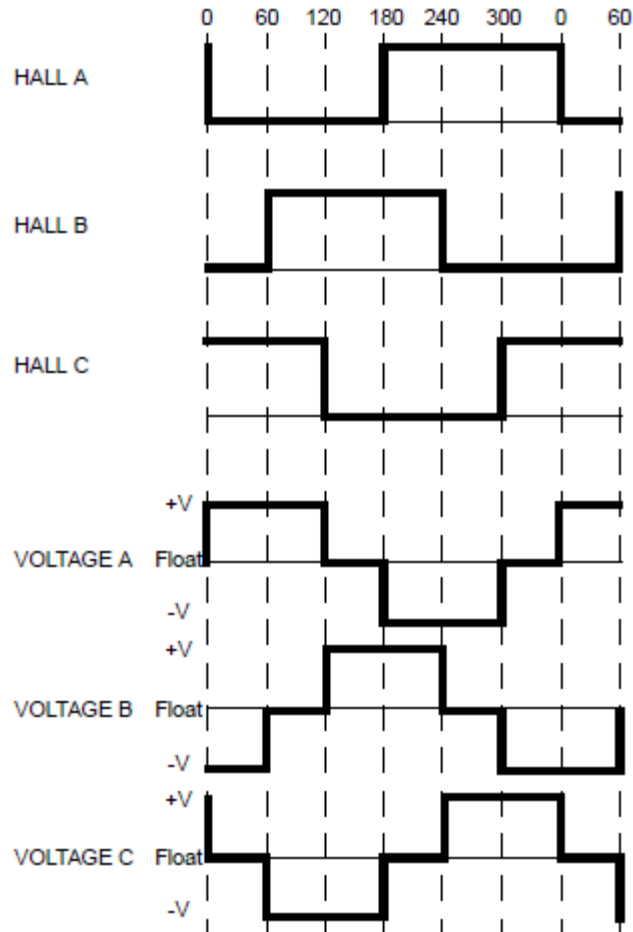


Figure 2.5: Ideal back EMFs and hall sensor signals (Yedamale, 2003)

This is usually referred to as motor's truth table as it determines which phases need to be energized for each Hall sensors transition. Figure 2.6 shows a cross section of the three-phase star connected motor along with its phase energizing sequence. The switches shown in Figure 2.7 are bipolar junction transistor where the MOSFET switches are more common. Table 2.1 shows the switching sequence, the current direction and the position sensor signals.

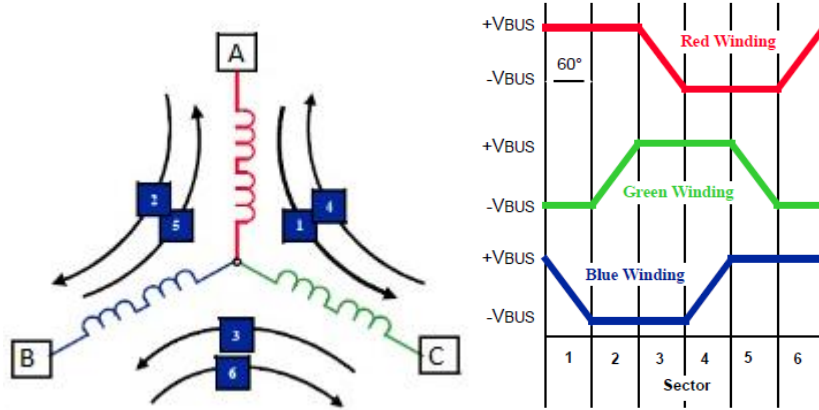


Figure 2.6: Cross section of the three-phase star connected motor with phase energizing sequence (W. Brown, 2009)

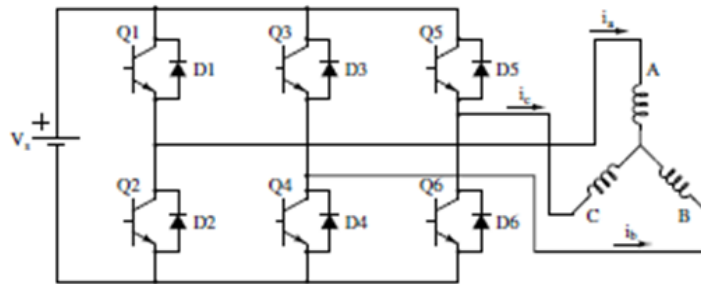


Figure 2.7: Six switches of BLDC drive scheme (Yedamale, 2003).

Table 2.1: Switching sequence

Switching interval	Seq. no	Hall			Switch closed		Phase current		
		1	2	3			A	B	C
0°-60°	0	1	0	0	Q1	Q4	+	-	
60°-120°	1	1	1	0	Q1	Q6	+		-
120°-180°	2	0	1	0	Q3	Q6		+	-
180°-240°	3	0	1	1	Q3	Q2	-	+	
240°-300°	4	0	0	1	Q5	Q2	-		+
300°-360°	5	1	0	1	Q5	Q4		-	+

2.6 Speed Controller

Speed controller as its name gives the desired speed based on the application needed. Generally, the speed controller can be classified into two categories which are open-loop and closed-loop speed controller. In open-loop mode of operations, there is no speed feedback incorporated in the system. The speed control is achieved via an external duty cycle control in order to set the speed reference, not through the speed feedback mechanism normally associated with the closed-loop system. The disadvantage of the open-loop speed controller is that the motor speed is unable to follow the specified reference if there are any load disturbances and parameter variations. Thus, the open-loop speed control is normally used for constant speed applications such as blower, fan and cooler in which the variable speed is not necessary. High performance drive systems should incorporate a closed-loop control system which provides system feedback and error correction mechanism. This would ensure an accurate and reliable speed control feature.

The commutation ensures proper rotor rotation of the BLDC motor. Consequently, the speed of the motor could be achieved by changing the applied voltage across the motor phases. Pulse width modulation (PWM) is used to apply a variable voltage to the motor windings. The effective voltage is proportional to the PWM duty cycle. The difference between the actual speed and reference speed is the input to the speed controller and, based on this difference, the speed controller adjusts the duty cycle of PWM pulses, which corresponds to the voltage amplitude required to keep the desired speed.

The speed controllers that can be used are the conventional PID controller or artificial intelligent controller such as FLC, Artificial Neural Network (ANN), Genetic Algorithm (GA), Adaptive control and other. Among all the techniques, FLC was given more focuses due to the application of linguistic rules in fuzzy logic which is in fact simpler than the other technique.

2.6.1 PID Controller

2.6.1.1 Overview of PID controller

A PID controller, which consists of Proportional, Integral and Derivative elements, is a control loop feedback controller that is widely used in industrial control systems. A PID controller responds to an error signal in a closed control loop and attempts to adjust the controlled quantity to achieve the desired system response. The controlled parameter can be any measurable system quantity such as speed, torque or flux. The benefit of the PID controller is that it can be adjusted empirically by adjusting one or more gain values and observing the change in system response. The error signal is formed by subtracting the desired setting of the parameter to be controlled from the actual measured value of that parameter. The sign of the error indicates the direction of change required by the control input.

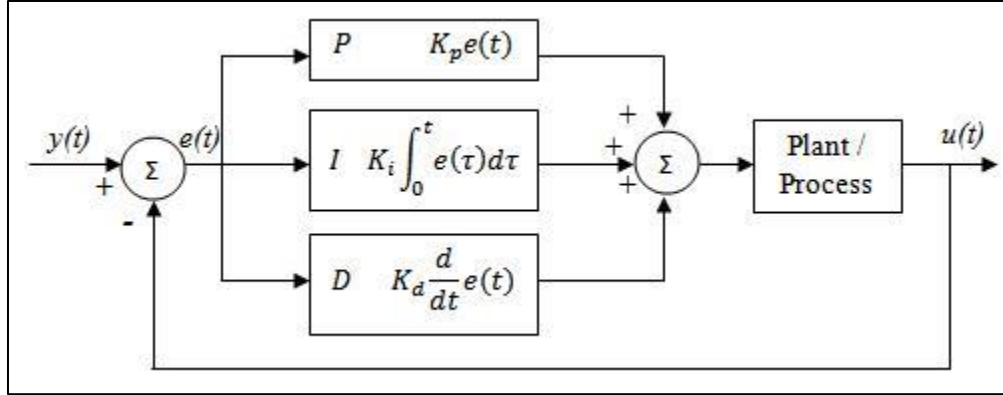


Figure 2.8: A block diagram of PID controller

Figure 2.8 illustrates that the PID controller scheme can be viewed as three correcting terms operating in parallel. The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (2.26)$$

where K_p is proportional gain, K_i is integral gain, K_d is derivative gain, e is error and t is instantaneous time.

Equation 2.26 shows that by multiplying the error signal with P gain will get the Proportional (P) term. Consequently, the control response of PID controller is proportional to the magnitude of errors. When the error signal is increase, the P term of the controller becomes larger to give more corrective action. As the time elapses, the overall error tends to reduce with effect of P term. In the most cases, the error of the controlled parameter can be approaching to zero but it does not converge. Hence, the P term has minor effect as the error get very close to zero. For the Integral (I) term of the controller is calculated by multiplying the I gain with the error signal. The I term

indicates the calculation of a continuous running of the error signal which can act to eliminate the steady state error. Next, the Derivative (D) term input is formed by subtracting the previous error with the present error. Therefore the D term of the controller is calculated by multiplying the change of error with a D gain. Hence, the D term of the PID controller is used to enhance the speed controller and response to the rate change of the error signal. Consequently, the D term of the controller produces more control output when the system error is changing faster. Note that the P, I and D gains are normally noted as K_p , K_i and K_d in the form of equation respectively. So the effect of K_p , K_i , and K_d in a closed-loop system are summarized in the Table 2.2.

Table 2.2: Effect of increasing parameter independently

Parameter	Rise time	Overshoot	Settling time	Steady-state error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Decrease significantly
K_d	Minor decrease	Minor increase	Minor increase	No effect in theory

2.6.1.2 Tuning PID Parameters

Tuning a control loop is a process of selecting its control parameters to meet the performance specifications. It is essentially important to fine tune the PID controller parameters in order to get the acceptable responses from the control systems. Several methods can be used for tuning al PID loop such as Ziegler-Nicholas, trial and error, software tools and Cohen-Coon. In this research, Ziegler-Nicholas is selected as tuning method for PID controller and briefly discussed here. The P gain of a PID controller determines the overall system response. For the initial step when first tuning the