SIMULATION OF SPEED CONTROL BRUSHLESS DC MOTOR USING GAUSSIAN FUZZY LOGIC CONTROLLER

NURLIANA BINTI ABD KARIM

A project report submitted in partial
fulfillment of the requirement for the award of the
Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY, 2014

ABSTRAK

Laporan projek ini membentangkan satu skim kawalan *Fuzzy Logic* bagi pemacu motor tanpa berus arus terus. Motor arus terus tanpa berus ini mempunyai beberapa kelebihan berbanding jenis motor lain. Walaubagaimanapun, pemacu motor tanpa berus arus terus ini mempunyai ciri tidak linear menyebabkan ianya sukar dikendali dengan menggunakan kawalan konventional seperti *Proportional-integral-differential Controller (PID)*. Oleh itu, untuk mengatasi masalah ini, kawalan *Fuzzy Logic* dengan fungsi keahlian *Gaussian* dibangunkan. Model matematik untuk pemacu motor arus terus tanpa motor diterbitkan. Pengawal ini direka untuk trek variasi rujukan kelajuan dan menstabilkan kelajuan keluaran semasa variasi beban. Keberkesanan kaedah yang dicadangkan disahkan dengan membangunkan model simulasi dalam perisian *Matlab Simulink*. Keputusan simulasi menunjukkan pengawal yang dicadangkan menghasilkan prestasi kawalan peningkatan yang ketara berbanding dengan pengawal *PID* bagi kedua-dua keadaan mengawal rujukan kelajuan perubahan dan variasi beban gangguan.

ABSTRACT

This paper presents a control scheme of a Fuzzy Logic for the brushless direct current (BLDC) motor drives. The BLDC motor has some advantages compare to others type of motors. However, the nonlinearity of this motor drive characteristics cause it is difficult to handle using conventional proportional-integral-differential (PID) controller. In order to overcome this main problem, Fuzzy Logic controller with a Gaussian membership function is developed. The mathematical model of BLDC motor is derived. The controller is designed to tracks variations of speed references and stabilizes the output speed during load variations. The effectiveness of the proposed method is verified by develop simulation model in Matlab Simulink software. The simulation results show that the proposed Fuzzy Logic controller (FLC) produce significant improvement control performance compare to the PID controller for both condition controlling speed reference variations and load disturbance variations.

CONTENTS

LIST OF TABLES

LIST OF SYMBOL AND ABBREVIATIONS

B	- Friction Coefficient
BLDC	- Brushless Direct Current
DC	- Direct Current
DSP	- Digital Signal Processing
e_a, e_b, e_c	- The Phase Back-EMF
e_{ab}, e_{bc}, e_{ca}	- Line-to-line Back-EMF
e_{ia}, e_{ib}, e_{ic}	- Error Phase Current
EMF	- Electromagnetic Field
FLC	- Fuzzy Logic Controller
$f_{abc}(\theta r)$	- Function of rotor position
i_a, i_b, i_c	- Stator Phase Current
$i_a$ref, i_b ref, $i_c$ref	- Reference Phase Current
I_{max}	- Reference Current
J	- Moment of Inertia
j_{th}	- Numbers of Neuron
K_e	- Back-EMF Constant
K_t	- Torque Constant
L	- Self-inductance
M	- Mutual Inductance
N	- North
PID	- Proportional Integral Derivative
R	- Phase Resistance
RPM	- Round per Minute

S - South

T_a, T_b, T_c - Phase Electromagnetic Torque

T_e - Electromagnetic Torque

T_L - Load Torque

TP - Peak Torque

TR - Rated Torque

V_a, V_b, V_c - Phase Voltage

V_{dc} - DC Supply Voltage

V_{ao}, V_{bo}, V_{co} - Reference to Midpoint of DC Supply Voltage

ω_m - Rotor Speed in mechanical

ω_r - Rotor Speed in electrical

Y - Star connection

Δ - Delta connection

θ_r - Rotor Position

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Project Overview

Nowadays, Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity [1]. As the name implies, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance-free motors were realized.

BLDC motors have many advantages over brushed DC motors and induction motors which is better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges. In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors [1].

The applications BLDC motor are widely used in many industries as growth as the rapidly developments in power electronic technology, manufacturing technology for high performance magnetic materials and modern control theory for motor drives [2]. Modern intelligent motion applications demand accurate speed and position control due to the favorable electrical and mechanical properties of BLDC motor. Many machine and control method have been developed to improve the performance of BLDC motor drives [3].

Based on previous studies in linear system model, controller parameters of proportional integral derivative (PID) controller are easy to determine and resulting good control performances. However, for nonlinear system model application such as BLDC motor drive, control performance of the PID controller becomes poor and difficult to determine the controller parameters. So that, Fuzzy Logic Control (FLC) will be used in order to improve the control performance.

In this project, a complete simulation model with FLC method for BLDC motor drive is proposed using Matlab/Simulink.

1.2 Problem Statements

Direct Current (DC) motor was chosen for the speed control applications due to the control simplicity on the intrinsic decoupling between the flux and the torque. As the name implies, there are physical limitations to speed and life time because of brush wear. However, BLDC have been produced to overcome this problem. Since there are no carbon brushes to wear out, a BLDC motor can provide significantly greater life being now only limited by bearing wear. This advantage make BLDC motor becomes popular in the industry but this motor is a non-linear system hence, need more complex speed controller than the DC motor.

By this reason, the Gaussian Fuzzy Logic controller will be developed to improve the performance of variable speed for BLDC motor since the system of this motor is non-linear system.

1.3 Project Objectives

The objectives of this project are:

i. To derive simulation model of BLDC motor using Matlab Simulation.
ii. To improve speed performances of BLDC motor such as reduces overshoot; reduce rise time and steady state error by using Fuzzy Logic controller.

1.4 Project Scopes

The scopes of this project are to simulate BLDC motor using Matlab Simulink software and develop the FLC that will be used to control the variable speed of the BLDC motor. The scopes of proposed FLC is limited to Gaussian membership function. The other membership function of FLC also will be develop to compare the effectiveness of the proposed controller.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In order to design and construct Gaussian Fuzzy Logic controller for BLDC motor speed, research in FLC need to be performed. This chapter would discuss the previous study of FLC that has been developing through the year.

2.2 Previous Case Study

Many approaches for designing controller based on the brushless DC motor has been proposed on the previous papers. The fuzzy speed controller was chosen by the designer due to their property. Fuzzy logic provides a useful methodology to create a practical solution for controlling complex system.

Siong T. C. *et al.* (2011) are proposed fuzzy logic controller for BLDC permanent magnet drives. The results shows that the fuzzy logic controller system provided a good dynamic performances in both simulation and experimental.

A novel digital control technique for brushless DC motor drives is to introduce a novel concept for digital control of trapezoidal BLDC motor. Rodriguez *et al.* (2007) found that the proposed digital controller is well suited for applications where speed ripple is not of significant importance.

This rapid control prototyping approach to fuzzy speed control of BLDC motor paper are study by Tuncay R. N. *et al.*. In this paper, fuzzy controller is successfully controlling the motor and the model based programming of DSPs. Fuzzy logic controller is founded more robust and fast than other conventional control techniques. It is also very simple and versatile.

This research has proposed a speed controller with adaptive fuzzy tuning method for the BLDC motor drives by Kwon C. J. *et al.* (2003). The simulation results have confirmed the good speed response and the efficiency of the proposed adaptive fuzzy logic scheme for changing motor parameter and load torque.

In this paper, a speed control for the BLDC motor based on a combination between sliding mode control and fuzzy logic is presented by Rusu C. The results of simulation and experiment show that the performance of the system drive has some advantages than using a pure siding mode control. The control precision of the system by using fuzzy sliding mode control is improved.

Cunkas M. *et al.* (2010) proposed realization of fuzzy logic controlled BLDC motor drives using matlab/simulink. In this study, it is seen that the desired real speed and torque values could be reached in a short time by fuzzy logic controller. The results show that MATLAB paired with simulink is a good simulation tool for modeling and analyze fuzzy logic controlled brushless DC motor drives.

In addition, Parhizkar N. *et al.* (2011) have presented direct torque control of BLDC motor drives with reduced starting current using fuzzy logic controller. Direct torque control offers some advantages such as simple algorithm, simplicity to implement, faster torque response, reduced torque ripple and less sensitivity to parameters variations. Fuzzy logic controller is used in order to eliminate overshoot exists in speed and torque responses. In addition by using fuzzy logic controller, starting current reduced due to reliability of this controller.

Brushless DC Motor Speed Control System Based on Fuzzy Neural Network Control has been proposed by Lv Y. *et al.* (2009). This paper presented fuzzy-neural network controller, which is based on Gaussian function, was successfully implemented herein in this study to achieve the control of the speed of the BLDCM. The simulation results show that the controller of the proposed method has a good adaptability and strong robustness when the system is disturbed, which is better than traditional PID control.

Oyedepo J. A. *et al.* (2011) have proposed Implementation of a fuzzy logic speed controller for a permanent magnet BLDC motor drive system. In this paper, the characteristics of permanent brushless DC motor, its steady state operation and its various torque-speeds/torque-current characteristics are studied. The speed of a BLDC Motor has been successfully controlled by using fuzzy logic controller technique. A comprehensive analysis of BLDC drive system has been performed by using fuzzy logic controller.

Chen W. *et al.* (2006) have presented sensorless control of BLDC motor based on fuzzy logic. The result shows that fuzzy logic controller can reduce the torque ripple. There is also has no neutral voltage, phase shifted or silent phase are required in this method which ensure its accuracy and stability.

Based on the previous case study, the researchers make a great effort to propose the good controller to control the speed of BLDC motor. Although the method is differ from each other, it is still can be conclude that fuzzy logic controller is the better controller compared to other conventional controller. Therefore, in this paper will use the fuzzy logic control as the controller of BLDC motor speed.

2.3 Brushless Direct Current Motor

The Brushless Direct Current (BLDC) motor is the ideal choice for applications that require high reliability, high efficiency, and high power-to-volume ratio. Generally speaking, a BLDC motor is considered to be a high performance motor that is capable of providing large amounts of torque over a vast speed range. BLDC motors are a derivative of the most commonly used DC motor, the brushed DC motor, and they share the same torque and speed performance curve characteristics.

The major difference between the two is the use of brushes. BLDC motors do not have brushes and must be electronically commutated. Commutation is the act of changing the motor phase currents at the appropriate times to produce rotational torque. In a brush DC motor, the motor assembly contains a physical commutator which is moved by means of actual brushes in order to move the rotor. With a BLDC motor, electrical current powers a permanent magnet that causes the motor to move, so no physical commutator is necessary. A BLDC motor is highly reliable since it does not have any brushes to wear out and replace.

2.3.1 Construction and Operating Principle

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and rotor rotate at the same frequency. BLDC motor does not operate directly off a DC voltage source. It consists of a rotor with permanent magnets, a stator with windings and commutation that is performed electronically. Normally three Hall sensors are used to detect the rotor position and commutation is performed based on Hall sensor inputs. There are two types of stator windings variants which are trapezoidal and sinusoidal motors.

2.3.1.1 Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as in Figure 2.1. Windings in a stator can be arranged in two patterns which is a star pattern (Y) or delta pattern (Δ). Most BLDC motors have three stator windings connected in star connection. The winding formed when each of these winding are constructed with numerous coils interconnected together. The stator windings construct into two types which is trapezoidal and sinusoidal motors.

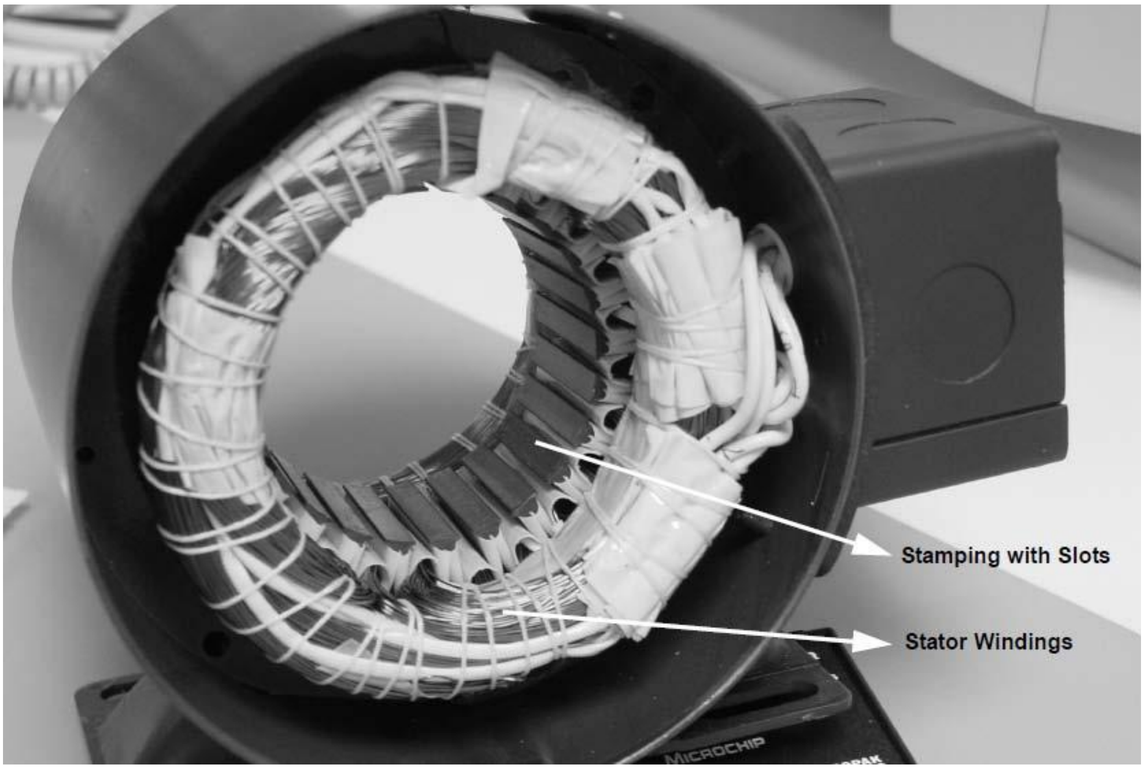
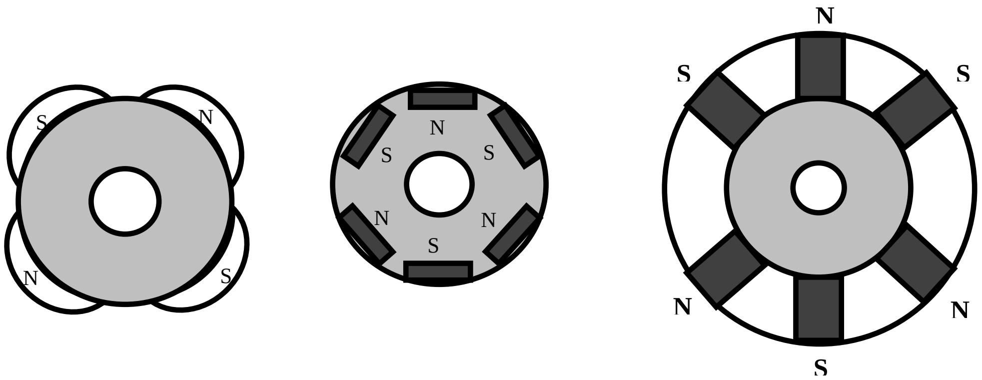


Figure 2.1: The stator of BLDC motor [13]

2.3.1.2 Rotor

The rotor of a typical BLDC motor is made out of permanent magnets. Depending upon the application requirements, the number of poles in the rotor may vary. Increasing the number of poles does give better torque but at the cost of reducing the maximum possible speed. Another rotor parameter that impacts the maximum torque is the material used for the construction of permanent magnet; the higher the flux density of the material, the higher the torque. Figure 2.2 shows cross sections of different arrangements of magnets in a rotor.



Circular core with magnets on the periphery

Circular core with rectangular magnets embedded in the rotor

Circular core with rectangular magnets inserted into the rotor core

Figure 2.2: Rotor Magnet Cross Section

2.3.1.3 Hall Sensor

Hall sensors work on the hall-effect principle that when a current-carrying conductor is exposed to the magnetic field, charge carriers experience a force based on the voltage developed across the two sides of the conductor. If the direction of the magnetic field is reversed, the voltage developed will reverse as well. For Hall-effect sensors used in BLDC motors, whenever rotor magnetic poles North (N) or South (S) pass near the hall sensor, they generate a HIGH or LOW level signal, which can be used to determine the position of the shaft. Most BLDC motor consists of three Hall Effect sensors and the combination of this sensor will produce the exact sequence of commutation. Figure 2.3 represents a cross section of a BLDC motor with rotor that has alternate North and South permanent magnets. There are two output versions by referring the physical position of the Hall sensors either at 60˚ or 120˚ phase shift to each other.

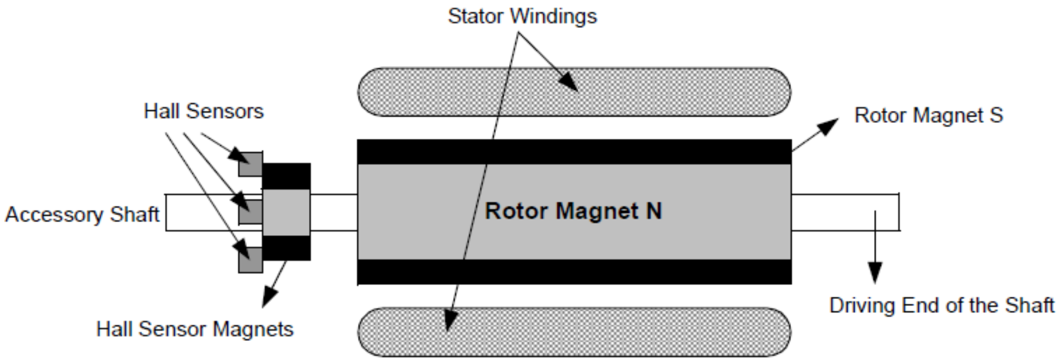


Figure 2.3: BLDC motor cross section [2]

2.3.1.4 Theory of Operation

Three windings on each commutation have different function. First windings will energized to positive power (current inflow into the winding), the second winding for negative (current out flow the winding) and the last winding is in a non-energized condition. The interaction between the permanent magnet and magnetic field generated by the stator coils will produce the torque. Basically, the peak torque occurs when these two fields are at 90˚ to each other and falls off as the field move together. In order to keep the motor running, the magnetic field produced by the winding should shift position as the rotor moves to catch up with the stator field.

2.3.2 Torque/Speed Characteristics

Based on the Figure 2.4, the BLDC motor can define using two torque parameters, a peak torque (TP) and rated torque (TR). The motor can be loaded up to the rated torque during continuous operations. The torque remains constant in a BLDC motor for speed range up to the rated speed. Meanwhile it capable to run up to the maximum speed which is 150% of the rated speed but the torque starts dropping during this situation.

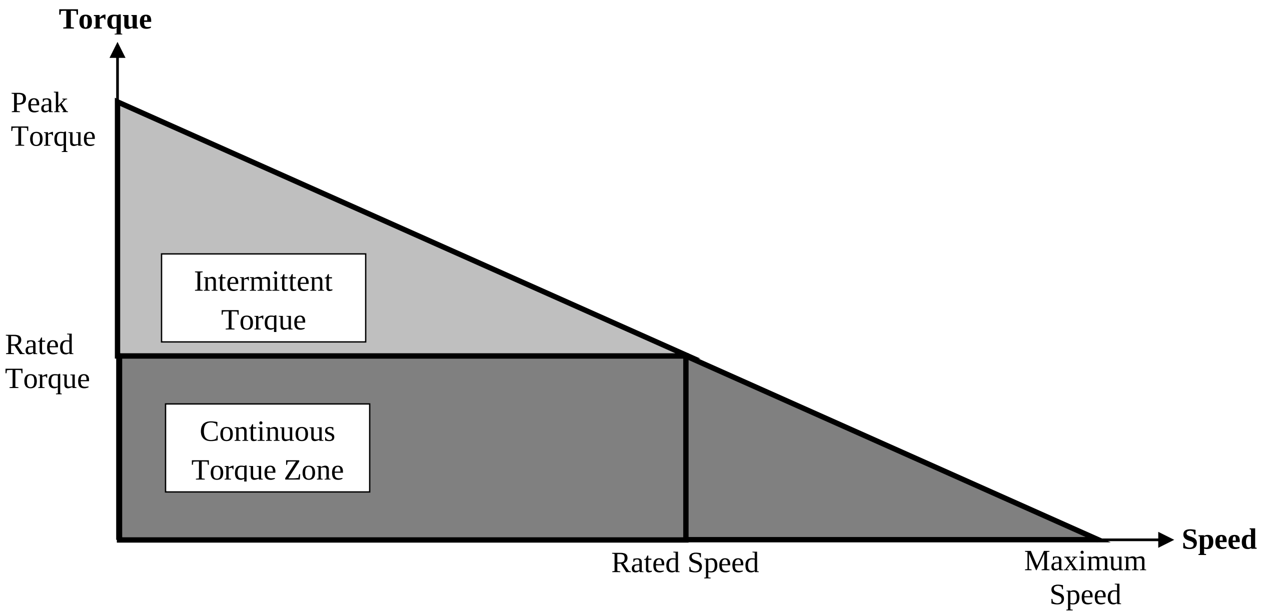


Figure 2.4: Torque/Speed Characteristic

2.3.3 Commutation Sequence

Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. In synchronous, with every 60 electrical degrees, the phase current switching should be updated. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles equals the rotor pole pairs. Figure 2.5 shows the Hall sensors signals with respect to back EMF and the phase current.

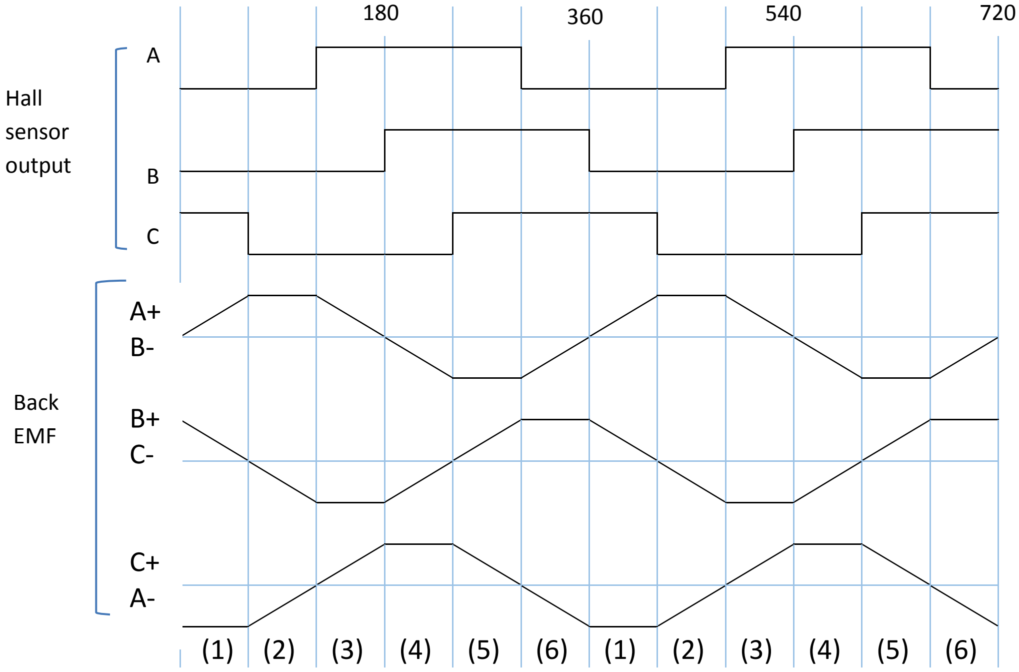


Figure 2.5: The hall sensor and trapezoidal back EMF waveforms of BLDC motor drive

2.3.4 Back EMF

According to Faradays law of electromagnetic induction, an EMF is induced or produced in a conductor and if a closed path is provided, the current will flows through it when a current carrying conductor is placed in a magnetic field. When the same thing happens in a brushless DC motor (BLDC) as a result of motor torque, the EMF produced is known as back EMF. It is so called because this EMF that is induced in the motor opposes the EMF of the generator.

This back EMF that is induced in the brushless DC motor (BLDC) is directly proportional to the speed of the armature (rotor) and field strength of the motor, which means that if the speed of the motor or field strength is increased, the back EMF will be increased and vice versa. When the DC motor is first started, there is no back EMF induced and there is maximum current flow from the DC generator or distribution lines to the motor armature and as a result the motor toque will be maximum. During normal operation (rated speed) of DC motor, the back EMF induced will be maximum which reduces the motor armature current to its minimum level and as a result the motor torque is also reduced. When the load on the motor is increased, the motor speed (RPM) is decreased and this reduces the back EMF. This decrease in back EMF automatically increases the motor torque thereby bringing the motor to its rated speed.

2.4 Fuzzy Logic Controller System

Fuzzy logic and fuzzy control theories added a new dimension to control systems engineering in the early 1970s. From its beginnings as mostly heuristic, somewhat ad-hoc, more recent and rigorous approaches to fuzzy control theory have helped make it integral part of modem control theory and produced many exciting results. Fuzzy logic is a technique to embody human like thinking which is much less rigid than the calculations computer generally perform into a control system. Fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusion from what they know. Meanwhile, conventional controller requires formal modeling of the physical reality of any plant.

Apart from that, fuzzy control incorporates ambiguous human logic into computer programs. It suit control problem that cannot be easily represented by mathematical model. Design of such controller leads to faster development and implementation cycles due to its unconventional approach.

There are four important elements in the fuzzy logic controller system structure which are fuzzifier, rule base, inference engine and defuzzifier. Firstly, a crisp set of input data are gathered and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This step also known as fuzzification. Afterwards, an inference is made base on a set of rules. Lastlty, the resulting fuzzy output is mapped to a crisp output using the membership functions, in the defuzzification step.

2.4.1 Fuzzification

Fuzzification is a process of making a crisp quantity fuzzy. Before this process is taken in action, the definition of the linguistic variables and terms is needed. Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language, instead of numerical values. A linguistic variable is generally decomposed into asset of linguistic terms.

There are different forms or shapes of membership functions in Fuzzy Logic such as triangular, Gaussian, trapezoidal and generalized bell. The most common type of membership function used by many applications is triangular. The type of the membership function can be context dependent and it is generally chosen arbitrarily according to the user experience. Figure 2.6 to Figure 2.9 shows the different types of membership function shape.

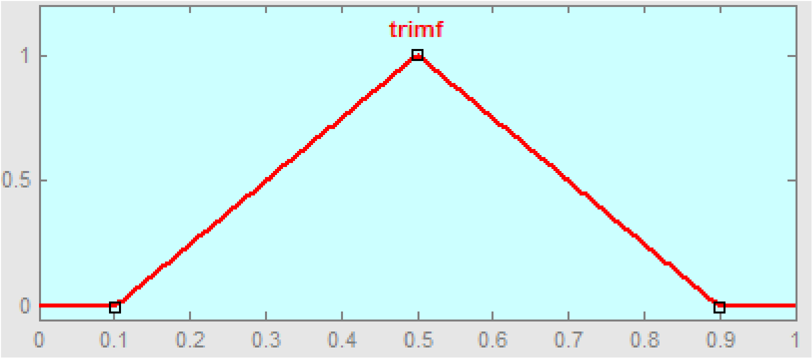


Figure 2.6: Triangular membership function shape

The equation of triangular membership can defined as follows;

$$triangle\ (x;a,b,c)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a\le x\le b\\ \frac{c-x}{c-b}, & b\le x\le c\\ 0, & c\le x\end{cases} \qquad (2.1)$$

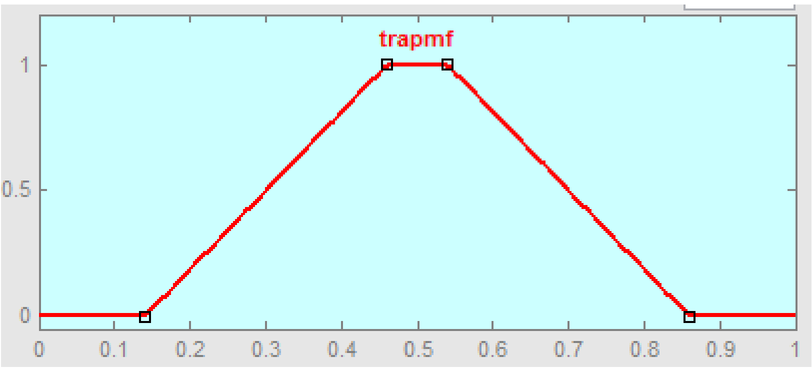


Figure 2.7: Trapezoidal membership function shape

The equation of trapezoidal membership can defined as follows;

$$trapezoid\ (x; a, b, c) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & d \leq x \end{cases} \tag{2.2}$$

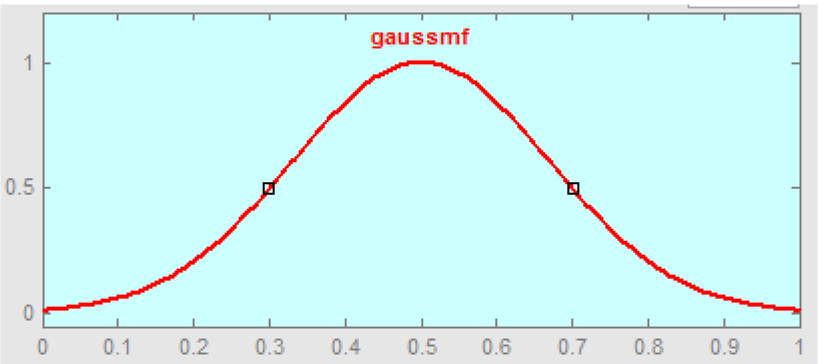


Figure 2.8: Gaussian membership function shape

The equation of Gaussian membership can defined as follows;

$$gaussian\ (x; c, \sigma) = \left\{ e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)^2} \right. \tag{2.3}$$

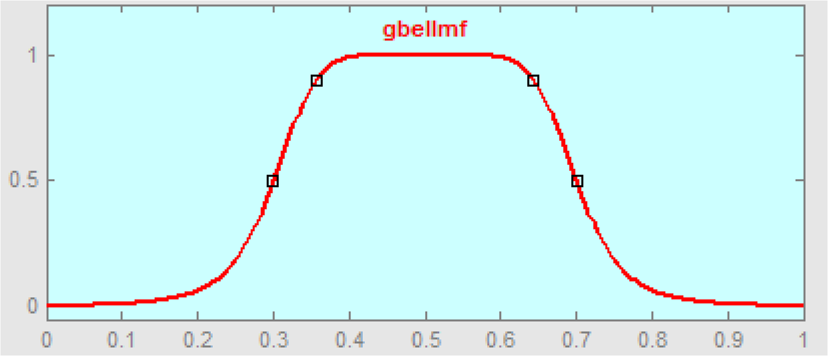


Figure 2.9: Generalized bell membership function shape

The equation of generalized bell membership can defined as follows;

$$bell\ (x; a, b, c) = \frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \tag{2.4}$$

2.4.2 Rule base

Fuzzy logic's linguistic terms are most often expressed in the form of logical implications, such as If-Then rules. These rules define a range of values known as fuzzy membership functions. A rule base (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control. Once the rules have been established, a fuzzy logic system can be viewed as a mapping from inputs to outputs.

2.4.3 Inference engine

In general, inference is a process of obtaining new knowledge through existing knowledge. In the context of fuzzy logic control system, it can be defined as a process to obtain the final result of combination of the result of each rule in fuzzy value.

There are many methods to perform fuzzy inference method and the most common two of them are Mamdani and Takagi-Sugeno-Kang method. Mamdani method was proposed by Ebrahim Mamdani as an attempt to control a steam engine and boiler in 1975. It is based on Lofti Zadeh's 1973 paper on fuzzy algorithms for complex system and decision processes. This method uses the minimum operation R_c as a fuzzy implication and the max-min operator for the composition. Suppose a rule base is given in the following form;

IF input x = A AND input y = B THEN output z = C (2.5)

After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It is possible and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function. It enhances the efficiency of defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of two dimensional function.

Meanwhile, Takagi-Sugeno-Kang method was introduced in 1985 and it is similar to the Mamdani method in many aspects. The first two parts of fuzzy inference process which are fuzzifying the inputs and applying the fuzzy operator are exactly the same. But, the main difference is that the Takagi-Sugeno-Kang output membership function is either linear or constant. A typical rule in Takagi-Sugeno-Kang fuzzy model has the form as follows;

IF input 1 = x AND input 2 = y THEN output z = ax + by+ c (2.6)

2.4.4 Defuzzification

After the inference step, the overall result is a fuzzy value. This result should be defuzzified to obtain a final crisp output. This is the purpose of the defuzzification component of a fuzzy logic controller system. Defuzzification is performed according to the membership function of the output variable.

There are many different methods for defuzzification such as Centroid of Gravity (COG), Mean of Maximum (MOM), Weighted Average, Bisector of Area (BOA), First of Maxima and Last of Maxima. There is no systematic procedure for choosing a good defuzzification strategy, but the selection of defuzzification procedure is depends on the properties of the application.

Centroid of Gravity (COG) is the most frequent used and the most prevalent and physically appealing of all defuzzification methods. The basic equation of Centroid of Gravity (COG) as below;

$$u_0 = \frac{\int_u \ \mu_{u\,(u)u\,du}}{\int_u \ \mu_{u\,(u)du}} \tag{2.7}$$

Where u_o is control output obtained by using Centroid of Gravity (COG) defuzzification method.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will divide into three phases. The first phase is understands the BLDC motor drive. The second phase is implementing the basic concept of fuzzy logic controller. The last phase is design and constructs the fuzzy logic controller for BLDC motor speed.

The proposed general block diagram for speed control of BLDC motor drive system using Gaussian fuzzy logic controller is shown in Figure 3.1.

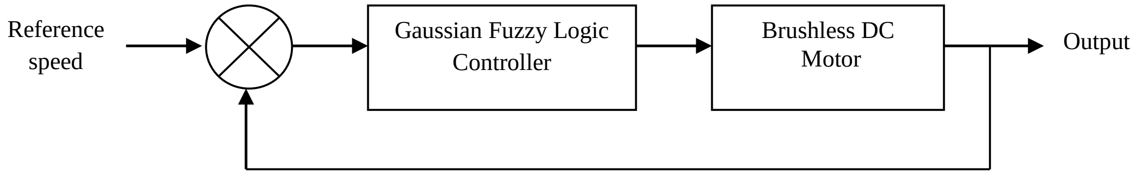


Figure 3.1: The block diagram of speed control using Gaussian fuzzy logic controller for BLDC motor drive system.

3.2 System Structure

3.2.1 Structure of BLDC Motor

The speed and torque characteristics of Brushless DC (BLDC) motors are very similar to a shunt wound *"brushed"* (field energized) DC motor with constant excitation. As with brushed motors the rotating magnets passing the stator poles create a back EMF in the stator windings. When the motor is fed with a three phase stepped waveform with positive and negative going pulses of 120 degrees duration, the back EMF or flux wave will be trapezoidal in shape.

BLDC motors are not strictly DC motors. It is use a pulsed DC fed to the stator field windings to create a rotating magnetic field and operate at synchronous speed. In figure 3.2 shown that, pole pair A is first fed with a DC pulse which magnetizes pole A1 as a South Pole and A2 as a North Pole drawing the magnet into its initial position. As the magnet passes the first magnetized pole pair, the current to pole pair A is switched off and the next pole pair B is fed with a similar DC pulse as pole pair A. The magnet will then rotate clockwise to align itself with pole pair B. By pulsing the stator pole pairs in sequence the magnet will continue to rotate clockwise to keep itself aligned with the energized pole pair.

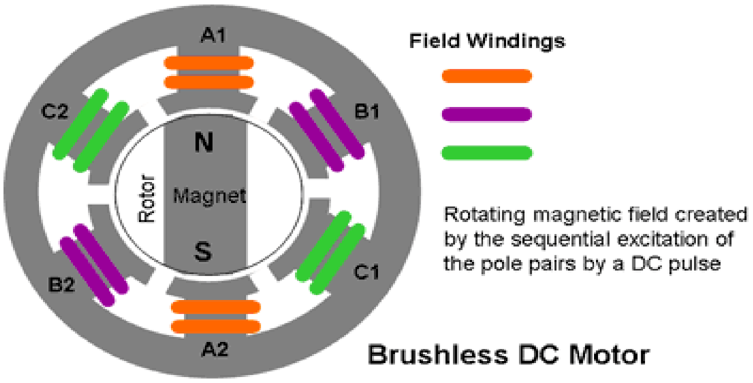


Figure 3.2: Disassembled view of BLDC motor. [14]

A six step inverter is used to generate the three phase supply and the electronic commutation between the three pairs of stator coils needed to provide the rotating field. Only two out of three pole pairs are energized at any one time. The speed of rotation is controlled by the pulse frequency and the torque by the pulse current.

The inverter current pulses are triggered in a closed loop system by a signal which represents the instantaneous angular position of the rotor. The frequency of the power supply is thus controlled by the motor speed. Rotor position can be determined by a Hall Effect device, embedded in the stator, which provide an electrical signal representing the magnetic field strength. The amplitude of this signal changes as the magnetic rotor poles pass over the sensor. Figure 3.3 shows the system for controlling the voltage and speed with the associated current and voltage waveforms superimposed on the circuits.

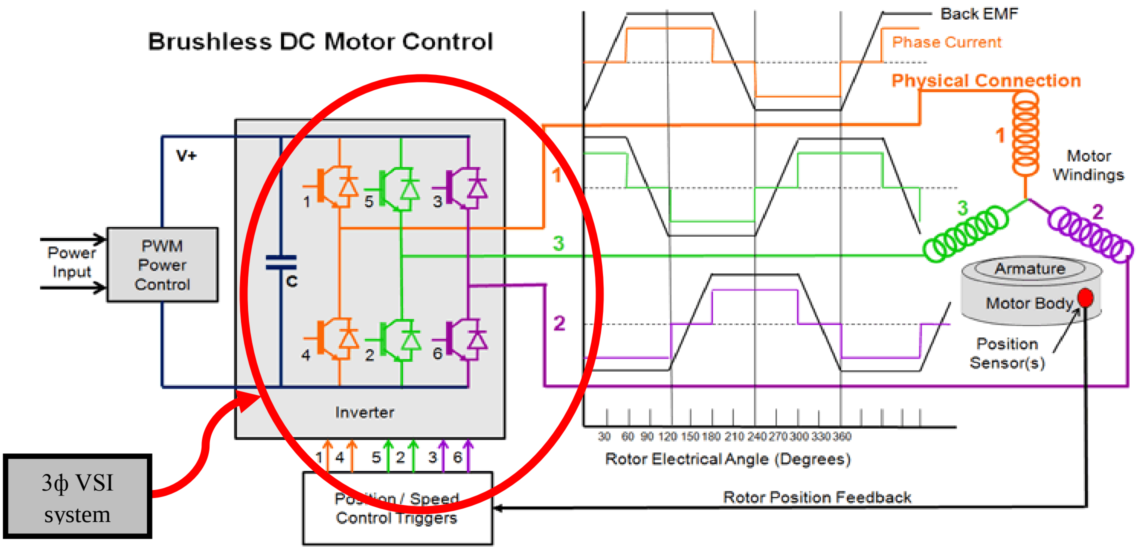


Figure 3.3: The system for controlling the voltage and speed with the associated current and voltage waveforms superimposed on the circuits. [14]

3.2.2 Modelling of a BLDC motor

The analysis of BLDC motor is based on the assumption for simplification and accuracy. The BLDC motor is type of unsaturated. The stator resistances for all the winding are equal and the self and mutual inductance are constant. Semiconductor devices of inverter are ideal and iron losses are negligible. Meanwhile, the back-EMF wave-forms of all phases are equal. Based on the equivalent circuit of BLDC motor and VSI system shown in Figure 3.3, the dynamic equations of BLDC motor using the assumption can be derived as

$$V_a = RI_a + (L - M)\frac{di_a}{dt} + e_a \tag{3.1}$$

$$V_b = RI_b + (L - M)\frac{di_b}{dt} + e_b \tag{3.2}$$

$$V_c = RI_c + (L - M)\frac{di_c}{dt} + e_c \tag{3.3}$$

Where

V_a, V_b, V_c = Stator phase voltages
i_a, i_b, i_c = Stator phase current
e_a, e_b, e_c =Phase back EMF
L = Self inductance
M = Mutual inductance
R = Phase resistance

The motion equation is defined as :-

$$\frac{d\omega_m}{dt} = \left(\frac{P}{2J}\right)(T_e - T_L - B\omega_r) \tag{3.4}$$

$$\frac{d\theta}{dt} = \omega_r \tag{3.5}$$

Where

T_e = The electromagnetic torque
T_L = Load torque (Nm)
J = Moment of inertia (kgm2)

B = Friction coefficient (Nms/rad)

ω_m = Rotor speed in mechanical (rad/s)

ω_r = Rotor speed in electrical (rad/s)

3.2.3 Modelling of a Trapezoidal Back EMF of BLDC motor

The trapezoidal back-EMF wave forms are modeled as a function of rotor position so that rotor position can be actively calculated according to the operation speed. The back EMFs are expressed as a function of rotor position (θ_r).

$$e_{abc} = f_{abc}(\theta_r) \times E \tag{3.6}$$

$$E = k_e \omega_r \tag{3.7}$$

Where (k_e) is back-EMF constant, $f_{abc}(\theta_r)$ are the function of rotor position.

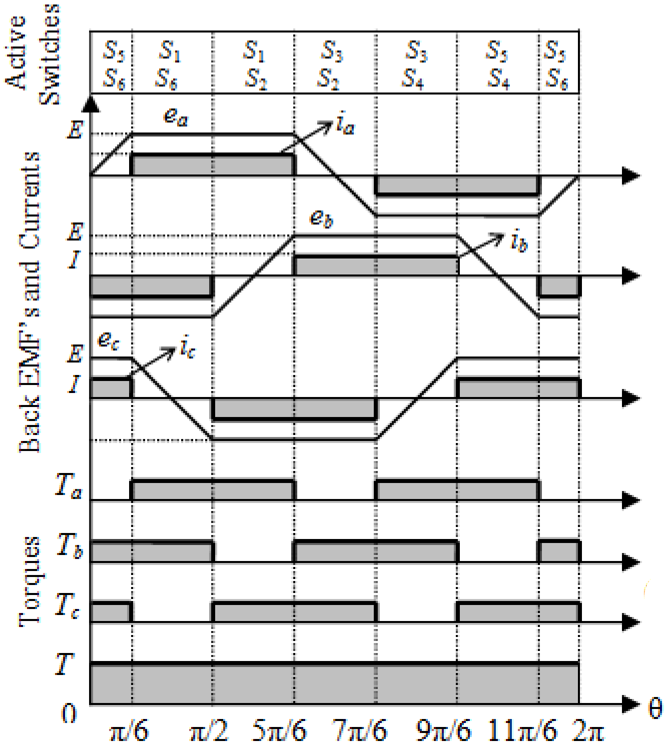


Figure 3.4: Trapezoidal back-EMF and phase current waveforms of BLDC motor drive

Figure 3.4 represent the back-EMF is a function of rotor position and has the amplitude. Based on the rotor position, the expression of the back-EMF can be generated as equation (3.8), (3.9) and (3.10) where named as trapezoidal shape functions with limit values between +1 and -1

$$f_a(\theta_r) = \begin{bmatrix} \left(\frac{6}{\pi}\right)\theta_r & \left(0 < \theta_r \leq \frac{\pi}{6}\right) \\ 1 & \left(\frac{\pi}{6} < \theta_r \leq 5\frac{\pi}{6}\right) \\ -\left(\frac{6}{\pi}\right)\theta_r + 6 & \left(5\frac{\pi}{6} < \theta_r \leq 7\frac{\pi}{6}\right) \\ -1 & \left(7\frac{\pi}{6} < \theta_r \leq 11\frac{\pi}{6}\right) \\ \left(\frac{6}{\pi}\right)\theta_r - 12 & \left(11\frac{\pi}{6} < \theta_r \leq 2\pi\right) \end{bmatrix} \tag{3.8}$$

$$f_b(\theta_r) = \begin{bmatrix} -1 & \left(0 < \theta_r \leq \frac{\pi}{6}\right) \\ \left(\frac{6}{\pi}\right)\theta_r - 4 & \left(\frac{\pi}{6} < \theta_r \leq 5\frac{\pi}{6}\right) \\ 1 & \left(5\frac{\pi}{6} < \theta_r \leq 7\frac{\pi}{6}\right) \\ -\left(\frac{6}{\pi}\right)\theta_r + 10 & \left(7\frac{\pi}{6} < \theta_r \leq 11\frac{\pi}{6}\right) \\ -1 & \left(11\frac{\pi}{6} < \theta_r \leq 2\pi\right) \end{bmatrix} \tag{3.9}$$

$$f_c(\theta_r) = \begin{bmatrix} 1 & \left(0 < \theta_r \leq \frac{\pi}{6}\right) \\ -\left(\frac{6}{\pi}\right)\theta_r + 2 & \left(\frac{\pi}{6} < \theta_r \leq 5\frac{\pi}{6}\right) \\ -1 & \left(5\frac{\pi}{6} < \theta_r \leq 7\frac{\pi}{6}\right) \\ \left(\frac{6}{\pi}\right)\theta_r - 8 & \left(7\frac{\pi}{6} < \theta_r \leq 11\frac{\pi}{6}\right) \\ 1 & \left(11\frac{\pi}{6} < \theta_r \leq 2\pi\right) \end{bmatrix} \tag{3.10}$$

The electromagnetic torque is defined by using back-EMFs as follows

$$T_a = \frac{e_a i_a}{\omega_r} \tag{3.11}$$

$$T_b = \frac{e_b i_b}{\omega_r} \tag{3.12}$$

$$T_c = \frac{e_c i_c}{\omega_r} \tag{3.13}$$

REFERENCES

[1] Padmaraja Yedamale, “Brushless DC (BLDC) Motor Fundamentals”, in *Microchip Technology Inc. AN885 Datasheet*, 2003, pp. 1.

[2] Raja Siti Nur Adiimah binti Raja Aris, “Simulation of a Variables Speed Brushless DC Motor using Neural Network Controller,” Universiti Tun Hussein Onn Malaysia, 2011.

[3] T.C Siong, B.Ismail, S.F.Siraj and M.F Mohammed, “Fuzzy Logic Controller for BLDC Permanent Magnet Motor Drives,” in *International Journal of Electrical & Computer Sciences IJECS-IJENS Vol:11 No.2,* Universiti Malaysia Perlis, Malaysia, 2011, pp. 13-18.

[4] Rodriguez F. and Emadi A., “A Novel Control Technique for Brushless DC Motor Drives,” in *IEEE Transaction on Industrial Electronics, Vol. 54, No. 5,* 2007, pp. 2365-2373.

[5] Tuncay R. N., Erenay Z., Yilmaz M., and Ustun O., “Rapid Prototyping Approach to Fuzzy Speed Control of Brushless DC Motor”, Istanbul Technical University, pp. 1-5.

[6] Kwon C. J., Han W. Y., Kim S. J. and Lee C. G., “Speed Controller with Adaptive Fuzzy Tuning for BLDC Motor Drive under Load Variations”, *SICE Annual Conference in Fukui,* 2003, pp. 2696-2699.

[7] Rusu C., “Fuzzy Sliding Mode Control of the Brushless DC Motor”, Technical University of Cluij, pp. 415-419.

[8] Parhizkar N., Shafiei M. and Kouhshahi M. B., “Direct Torque Control of Brushless DC Motor Drives with Reduced Starting Current Using Fuzzy Logic Controller”, *International Conference on Uncertainty Reasoning and Knowledge Engineering,*2011, pp. 129-132.

[9] Sharmila B. and Devarajan N., “Neuro-Fuzzy Controller for Networked DC Motor Control”, *European Journal of Scientific Research,* 2011, pp. 219-228.

[10] Lv Y., Fan H., Zou Q. and Wan J., “Brushless DC Motor Speed Control System Based on Fuzzy Neural Network Control”, *Proceedings of the 2009 International Workshop on Information Security and Application,* 2009, pp. 173-176.

[11] R. Akkaya, A.A. Kulaksız, and O Aydogdu, “DSP implementation of a PV system with GA-MLP-NN based MPPT controller supplying BLDC motor drive”, *Energy Conv. and Management 48*, 210-218, 2007.

[12] A. Pooja and P. Arpita, “Brushless DC Motor Speed Control Using Proportional-Integral and Fuzzy Controller”, *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*,68-78,2013.

[13] Techzone (2013), Microcontroller *Solution*, Retrieved on March 3, 2012, from http://www.digikey.com.

[14] Electropaedia (2005), *Battery and Energy Technology,* Retrieved on March 25, 2012, from http://www.mpoweruk.com