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TECHNOLOGY)**

**Extended Kalman Filter for estimation of rotor Position and Speed of sensor-
less Brushless DC Motor**

MSc Thesis for the Partial Fulfillment of
Master of Science in Electrical Automation and Control Technology Management

By,

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Extended Kalman Filter for estimation of rotor Position and Speed of sensor-less Brushless DC Motor

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BY

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Declaration

I hereby affirm that the work being offered in this thesis is Extended Kalman Filter for estimation of rotor Position and Speed of sensor-less Brushless DC Motor the unique work of my own, has not been existing for a degree in this or other universities.

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Thesis Title on

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Abstract

Fuzzy logic controller have been used to control speed based on the error generated from the reference and estimated speed. The measured data and disturbance serve as the extended kalman filter input. In a simulation, as I have looked from the result how the noise covariance matrices could be controlled. BLDC motor requires sensor to detect the speed and position. The main objective of this thesis is design and simulation of extended kalman filter based sensor less brushless direct current. In this thesis, a three-phase BLDC motor speed is accurately estimated without the usage of sensors by using an extended kalman filter. Consequently, the extended kalman filter-based three-phase inverter function and mathematical machine modeling used in the motor's actual operation. The estimation that results is simulated to provide an accurate estimation of the brushless dc motor entire state. The outcome showed a satisfactory speed control reaction during a 0.1Nm disturbance at a 0.1s step change to provide good results; thus, the speed controller's design produces a good ability to reject disturbances many simulations were run in the presence of disturbance and parameter variation. MATLAB/Simulink is used to model the system.

Keywords:3-phase BLDC motor, trapezoidal emf, sensorless control ,extended kalman filter, FLC controller.

List of Abbreviation

BLDCM	Brushless direct current motor
DC	Direct current
BLAC	Brushless alternate current
AC	Alternate current
EKF	Extended Kalman Filter
KF	Kalman Filter
UKE	Unscented kalman filter
PID	Proportional plus integral plus derivative
EMF	Electro motive force
MMF	Magneto motive force
VSI	Voltage source inverter
CSI	Current source inverter
DTC	Direct torque control
KD	Derivative gain
FLC	Fuzzy logic controller
PWM	pulse width modulation
PMSM	permanent magnet synchronous motor

List of Symbols

R	Resistance
L	Inductance
M	Mutual inductance
J	Moment of inertia
P	Number of poles
b_k	Back-EMF constant
k_t	Torque constant
v_{dc}	DC bus voltage
B	Frictional coefficient
e	Error
ω_n	Mechanical speed
T_e	Electrical torque
T_L	Load torque
$F\theta_e$	Function of electrical angle
v_a, v_b, v_c	Phase voltages
i_a, i_b, i_c	Phase currents
e_a, e_b, e_c	Motor phase back EMFS

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CHAPTER ONE

Introduction

1.1 Background

Permanent magnet BLDC motor drives require a rotor position sensor to properly perform phase commutation. The Brushless DC motor is a particular type of Permanent Magnet Synchronous motor with quasi-rectangular current waveforms and a trapezoidal back EMF.

BLDC is rotated by direct current (DC) electricity via an inverter or switching power source that converts the DC energy into alternating current (AC) to drive each phase of the motor via in a closed loop controller. The controller delivers pulsed current to the motor windings, which controls the torque and speed of the motor.

This is owing to the fact that a brushless DC motor (BLDCM) must always be viewed as a combination of a controller and a motor because it cannot work without one and the controller needs DC input. The motor is an electromagnetic rotating device that runs on pulsed AC, whereas the controller is a static unit that converts DC into pulsed AC. A DC voltage serves as the controller's input. Motor electromagnets are fed 2- or 3-phase AC by the controller, which transforms DC voltage. Be aware that the controller's AC output is not a sinusoidal, pure AC wave, but a rectangular or pulsed waveform instead.

When the stator electromagnets are powered by pulsed AC from the controller, the polarity of the electromagnets is continuously changed in a sequential manner, which in turn causes the stator magnetic field to rotate. Due to magnetic pull, the permanent magnets in the rotor rotate in accordance with the stator's revolving field. Thus, the motor operates similarly to a synchronous motor. This motor is commonly referred to as a DC synchronous motor because its main power source is a DC controller [1]. Brushless direct current (BLDC) motors has many advantages[1] such as removal of sparking, better speed versus torque characteristics, quieter operation, wider speed ranges, long life, reduced noise rugged construction and robust construction. Numerous studies have focused on the proper commutation of BLDC motors speed variation, reduction of torque ripples, and energizing of phases [1].

Due to their high efficiency, silent operation, compact design, durability, and little maintenance requirements, brushless dc (BLDC) motors are preferred as small horse power control motors[2]. Although there have been issues with these motors' ability to operate at

variable speeds over the past few decades, production of permanent-magnet brushless electric motors and ongoing technological advancements in power semiconductors, microprocessors, adjustable speed drivers, and control schemes have enabled reliable, affordable solutions for a variety of adjustable speed applications[3]. Because of its many advantages, which include their high efficiency, rapid dynamic response, longer operational life, low noise, and high torque-to-weight ratio [4] ranges, the usage of BLDC motor drives in consumer goods and industrial applications is increasingly widespread.

BLDC motors do not have brushes, so that commutation is performed electrically. Based on feedback from the rotor position, a driving amplifier and semiconductor switches are utilized to change the current in the windings [1]. To detect the actual rotor position, BLDC motors frequently use internal or external position sensors as a result, the motor increases in cost, size, and durability. Both approaches lower the cost of variable speed drives [5]. To achieve the required dynamics, control algorithms are created and applied in the control method. Several sensors-less control strategies have been developed in order to enhance the performance of BLDC motor drives. The majority of devices in use today sense the rotor position every 60 electrical degrees, this is essential for sensor less drives that must perform current commutations and so need highly accurate speed and rotor position estimates. These tactics do not [1], the rotor position cannot be continually estimated by them. Between the controller and the phase inverter circuit, the gate driver serves as a connecting component. The phase inverter circuit's (MOSFETs) receive an amplified gate drive current from the gate driver, which also receives PWM signals from the controller [6]. The dc to ac converters, commonly known as inverters, those are separated into two groups: voltage source inverters (VSIs) and current source inverters, depending on the kind of supply source and the corresponding topology of the power circuit (CSIs) [7].

The phase inverter circuit is built around a metal oxide semiconductor field effect transistor and consists of switches for each phase of the BLDC motor (MOSFET). A three-phase BLDC motor control system uses six MOSFETs to control the high and low sides of each phase. [6]. Fast switching between the device's highest and lowest resistance states is principally accomplished by the MOSFET operating in switch mode in the circuit. The least squares-based observer known as the Kalman filter best predicts system states. The EKF is a

nonlinear problem solution that was derived from the Kalman filter[4]. The extended Kalman filter has been used to forecast the rotor position and speed of permanent magnet motors with sinusoidal or trapezoidal EMF (PM). With motors that have rectangular currents, it cannot be used[5]. A unique EKF technique has been created in this study and an estimator has been applied to a number of motors. Appliances makers are now forced to employ brushless dc motors in their goods due to recent legislation that mandates them fulfill efficiency standards. The complexity of controlling these applications has increased due to brushless dc motors, though. To choose the correct commutation sequence, brushless dc motors, on the other hand, typically need some kind of position transducer. However, in these budget-conscious applications, the extra cost of adding position transducers is neither acceptable nor practical. Instead, the machine had been built with standard Hall sensors.

Torque information can be derived[6], For standard 3-phase BLDC motors, a six-switch inverter BLDC motor is employed [7], due to its inherent advantages of having a straight forward structure and reliable operation. Numerous artificial intelligence-based techniques have been put forth by researchers to explain for the nonlinear parameter change of BLDC motors[8]. Fuzzy Logic-based control structures have been presented on several occasions as an alternative to these controllers[9].

Hysteresis current control is used for generating the switching pulses. Among the various current control techniques, HCC is the most extensively used technique because of the non-complex implementation, outstanding stability, absence of any tracking error, very fast transient response, inherent limited maximum current, and intrinsic robustness to load parameters variations[10][11]. The outputs of the hysteresis blocks are directly fed as the firing pulse of VSI switches[10][12].

In this thesis, MATLAB/Simulink was used to design the three-phase BLDC motor and other elements of the mathematical model.

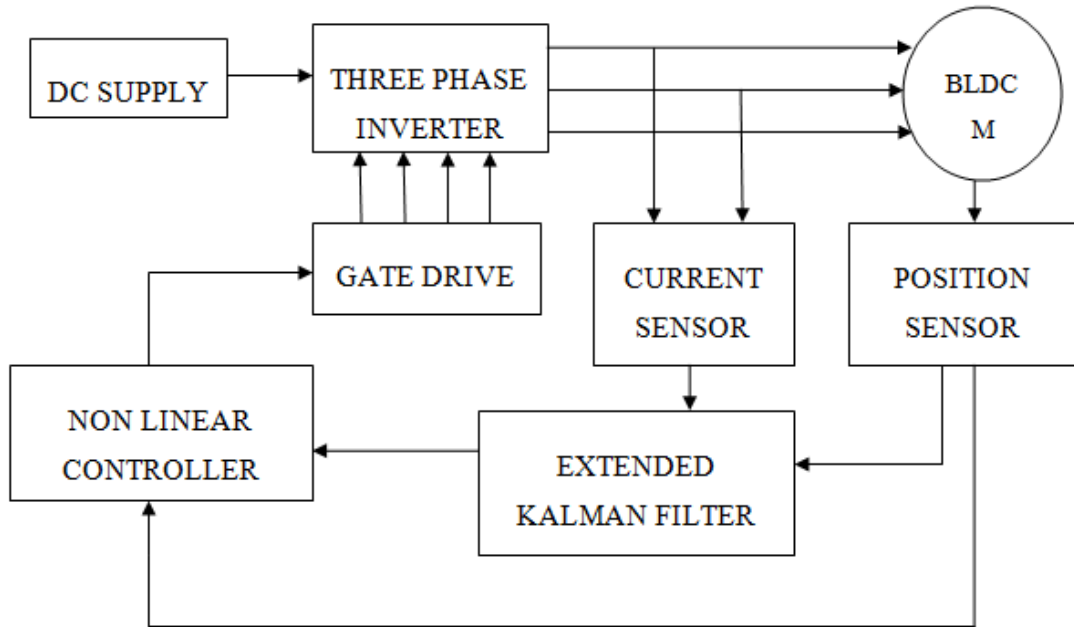


Figure 1.1 block diagram of BLDC motor with EKF[5]

1.2 Statement of the problem

Hall Effect sensor is required to detect rotor speed and position of Brushless dc motor. The sensor that used to detect rotor speed and position make motor system sophisticated, unreliable, and expensive. The sensor-less control technique employed in this thesis is based on the notion that the rotor position could have been predicted using an extended Kalman filter (EKF). Several sensor less driving strategies have been tried in the past to replace the cost and ineffective position sensing for BLDC motors; these techniques include flux estimates, voltage back-EMF sensing, back-EMF integration, and motor modification approaches all of the approaches listed above work inadequately at low speeds these methods' variable speed ranges need to be improved. The estimators listed above are also having difficult to linearize nonlinearity in mechanical objects and designing model parameters. By using an extended Kalman filter, all of these above flaws are eliminated.

1.3 Objective

1.3.1 General objective

The main objective of this thesis is to estimate rotor Position and Speed of sensor-less Brushless DC Motor Using Extended Kalman Filter and Fuzzy Logic Controller.

1.3.2 Specific objective

- To simulate mathematical model of brushless DC Motor by using MATLAB- Simulink Software.
- To apply fuzzy logic controller for speed control of brushless DC motor.
- To study construction feature of three-phase BLDC motor.
- To apply extended kalman filter algorithm to estimate speed and rotor position of BLDC Motor.

1.4 Significance of the thesis

- ❖ To shows easiest method of controlling sensor less three-phase BLDC motors.
- ❖ To model and simulate sensor less control of the BLDC motors based the EKF

1.5 The scope and limitation

In this thesis, extended kalman filter is used to estimate sensor less BLDC motor speed

MATLAB/Simulink software and a mathematical model of the device are used to simulate the function of a three-phase inverter; it is based on the extended kalman filter sequence produced in a three-phase BLDC motor's stator windings. This thesis is primarily concerned with three-phase BLDC motor speed control using an extended kalman filter and sensor less technology. The analysis of MATLAB/Simulink is the sole focus of this thesis' results. Due to the high material cost, the implementation is not carried out.

1.6 Methodology

In order to be used as a step in the future, several significant references will be scanned and cited as part of the literature review. The sensor-less control of the conventional permanent magnet motor system was the focus of an updated study model and analysis. First, study the three-phase permanent magnet synchronous motor design futures. To accomplish the main aim, which is sensor-less machine control, the three-phase machine model was developed in

MATLAB simulation. The extended kalman filter's equation is created from a mathematical model. The second step is to model and analyze sensor-less three-phase BLDC motor control using the extended kalman filter.

1.7 Thesis organization

There are six chapters in this thesis, Chapter one, introduction Chapter two, Literature reviews. Chapter three, construction future of three-phase BLDC Motor and its mathematical modeling, Chapter four, controller design .Chapter five, this chapter presents a MATLAB simulation model and uses the MATLAB/Simulink library to build block models of the suggested model control. Additionally, there is simulated sensor-less control, chapter six, conclusion and recommendation.

CHAPTER TWO

LITERATURE REVIEW

Electric machines are used in industries to perform mechanical work and to generate electricity in power plants. A fundamental electric machine is the DC machine [13]. Permanent magnet brushless DC (PMBLDC) motors are one of the electrical drives that are swiftly gaining popularity due to their exceptional efficiency, strong dynamic response, and minimal maintenance requirements. The brushless dc motor's (BLDCM) electromotive force (EMF) and current waveforms are, respectively, quasi-rectangular and trapezoidal. Three Hall sensors are used as position sensors in accordance with industry best practices for current commutations every 60 electrical degrees[14].

Estimated speed was used as the feedback signal in the control circuits to create a sensor-free speed control system. [14] The EKF model enables optimization for all loads and speed ranges by predicting speed, flux, load torque, and stator resistance at low speeds [15]. Electronic commutation is used in brushless motors in place of employing brushes to commutate the armature current [2].

Hysteresis controllers are intrinsically robust to system parameters, exhibit very high dynamics, and are suitable for simple implementation[16]

The BLDC motor is a revolving electric device with a three-phase stator. Like an induction motor, the rotor has surface-mounted permanent magnets. There are no brushes on the rotor, and the commutation is done electronically at a certain rotor position[17].

It is crucial to determine the exact value of torque, which is defined by the waveforms of the back-EMF, as the torque characteristics of BLDC motors play a key role in the development of the BLDC motor drive system.[18].

Increased dependability and fault-tolerance capabilities in safety-critical domains, like airplane use, are made possible by the availability of sensor-free operation with multi-phase motors.[19].

Three independent DC-AC converters can be used to generate three-phase AC power [20]. A near sinusoidal MMF distribution requires the use of many slots, one for each pole and phase [20].

When a permanent magnet synchronous machine is used, a focused winding design produces behavior resembling that of a BLDCM[21].

In some applications where the harsh exterior conditions limit the use of those sensors in a reliable manner, sensor-less control is the only choice [8].

In the stationary reference frame, one can regulate phase currents or their component phases, in this case, the common ramp-comparison current[21], therefore, it would be advantageous to have a control system that does not require a mechanical position sensor, or "sensor free control system. Numerous approaches have been put out during the many years of research on this topic. The majority of them have relied on the detection of the speed-dependent back electromotive force (EMF). At medium and high speeds, this procedure is successful; at zero and low speeds, it is unsuccessful. This occurs as the back EMF rapidly declines and gradually disappear [4].

It is also possible to raise the power in the same frame as the number of phases increase. [22], Fault tolerance is required in order to enable fail functioning modes due to the high reliability requirements for safety-critical applications. One technique to increase the fault tolerance of electrical drive drives is to use more phases because performance loss is expected when utilizing more of them [23].

The motor has been simulated using switching functions and dynamic modeling. Hysteresis current control is also used in the internal loop of the speed and torque control system to provide constant torque and maximize the motor's maximum torque capabilities[19]. Thus, it is appropriate to use this model of BLDC motor in sensitive and high performance applications. Zero-sequence sinusoidal input improves dc bus utilization, but as the number of phases increases, this benefit quickly diminishes [21],[24],[25]. BLDC motor drives need. Due to their intrinsic advantages and detecting advantages, Magnetic field sensing-based angular motion sensors stand out. The direction of the rotor is determined by three Hall-effect sensors that are built into the stator and set at a 120-degree angle on a PCB that is fixed to the non-driving end of the enclosure cover. The stator windings must be energized in a precise order for a BLDC motor to turn. The magnetic rotor Hall sensor's output signal is HIGH Level ('1') when the sensor's North Pole is close by. greater power is generated by the motor as the

number of Pole-Pair increases [26],[27].

The second method for efficient BLDC motor control is sensor-less control. By simply determining the rotor position from the motor, this technique does away with the requirement for sensors. These position sensors can be removed to reduce costs and increase dependability. Position sensors are used in sensor-less drives, which only employ electrical signals.

There is a lot of study being done on sensor-less drives due to the drawbacks of employing Hall sensors. When system dynamics are not very demanding and only variable speed control (i.e., no positioning) is needed, position sensors can be completely disregarded, lowering the cost and motor assembly size (i.e., slowly or at least predictably varying load). A PM brushless drive is referred to as a sensor less drive if it solely uses electrical measurements rather than position sensors. In spite of the recorded terminal voltage's strong signal-to-noise ratio, low speeds cannot be identified since the back-EMF is zero at rest and inversely proportional to speed.

Because of this, all back-EMF-based sensor less approaches have limited low-speed performance, necessitating the adoption of an open-loop starting method[4] . As described in the preceding sections, control procedures for non-linear systems are different from those for linear systems. To reduce chattering and increase the stability of the regulated system, fuzzy logic is employed[28]. Fuzzy boundary layer technology is created to allow a smooth transition to the similar control. Better disturbance rejection abilities and less overshoot in the speed response, traditional FLC controllers have severe limitations in managing non-linear systems. This is a result of the nonlinear systems' unpredictable behavior, whose state can vary quickly due to the system's variables[29]. When conventional and fuzzy controller simulation results are compared, it becomes clear that the FLC performs better dynamically and is more resilient to changes in the parameters of industrial speed control drive applications [8]. For instance, an FLC regulator won't be able to control a motor whose resistance varies quickly. The complexity of linear systems, including their modeling, necessitates the use of additional control techniques and the implementation of additional controller types whose control laws are adaptive, that is, they consider the state of the system to be controlled as well as any potential variations in time, which is a characteristic of observing systems[30].

Fuzzy logic controller (FLC) has demonstrated its capability to handle plant nonlinearity without the requirement of its mathematical model [9]. FLC is constructed from four main components – Rule Base, Inference Mechanism, Fuzzification and Defuzzification Interface[31]

To calculate flux and speed with accuracy at zero and very low speeds, a suitable EKF estimator is proposed. The technique uses two EKF algorithms with speed-sensor-less direct vector control, alternating between them at each sample time. The estimation of more parameters is required while switching methods. An essential difficulty in speed sensor less IM control described in the thesis is the estimate of rotor and stator resistances in steady and transient states. [15]. They offer a rough representation of the state vector of the control system. EKF algorithms can be used to estimate the state vector of nonlinear systems, as is the case with BLDC motors, which are nonlinear systems.[22].

The EKF method easily manages the limits related to the imperfections and non-linearity of the model used and is part of the methods of used in wide applications regarding the sensor less control[23],[6]. The Extended Kalman Filter (EKF), a more complex version of the Kalman filter, was utilized to create the control algorithm for the motor because BLDC motors are non-linear systems. [24],[25]. Controlling the speed of BLDC motors is essential. Since many of the power electronic circuits utilized for this have large switching losses, the total system efficiency is reduced.

The most common type of closed-loop controller is the PID controller [36]. The method is based on the speed discrepancy between the real speed error and the reference speed, PID parameters. K_p percentage growth. The integral gain has an effect on the system's efficiency K_i and the derivative gain K_d [27]. Nonlinear loads generate harmonic currents and voltages in power systems[38]

Normally a mathematical model The Fokker-Planck equation, commonly known as the suboptimal equation, is solved by the EnKF estimating system using ensemble integration techniques. The error statistics are anticipated using Monte Carlo. PWM techniques with a constant DC-link voltage or PAM techniques with a variable DC-link voltage are two popular methods for driving BLDC motors. system is designed using a PID controller, and the sys-

tem's performance is assessed using a set of applied PID parameter values before the best values are decided upon.[26].

Researchers have proposed a variety of artificial intelligence-based solutions to account for the BLDC motor's nonlinear parameter change. Fuzzy Logic-based control structures have been presented on several times as an alternative to these controllers[9].

For brushless direct-current (BLDC) motor speed control, a modified distinct evolutionary (DE) algorithm-based proportional integral (PI) controller is provided. The beginning rule, the multivariable fitness function, and the adaptive mutation factor are used to alter the DE algorithm to alter the parameters of the PI controller [37] The output of the PID controller adds three terms: a proportional, an integral, and a derivative; hence, the name. The value of the input-output error e determines each of these terms [25]

2.1 Summary of the literature review

High torque, high efficiency, and high power density are just a few benefits that BLDC motors provide. They are also appropriate for high performance applications. Compared to conventional DC and induction motors. There are several methods for estimating the position and speed of BLDC Motors. Some of them include sensor-less back-EMF zero crossing detection techniques and hall-effect sensors. Hall-effect sensors increase the mechanical unpredictability, expense, and unreliability of the motor system. Methods for detecting back-EMF zero crossings are effective at slow speeds. Additionally, they face challenges while attempting to linearize nonlinearity in mechanical objects and design parameters. There are various techniques for estimating the speed and position of BLDC Motors. Some of them include back-EMF zero crossing detection techniques and hall-effect sensors without sensors. The motor system is more unstable, mechanically unpredictable, and expensive because of the hall-effect sensors. Techniques for detecting back-EMF zero crossings at slow speeds work well. They are also having problems linearizing nonlinearity in mechanical objects and design parameters

CHAPTER THREE

MATHEMATICAL MODELING

3.1 Features of three-phase BLDC motor construction

The Brushless DC (BLDC) Motor are electronic commuted motors but brushed DC motors are mechanically commuted motors[30]. The magnets in this system's motor are "inside-out" as opposed to brushed DC motors since the rotor employs one (or more) permanent magnets and the stator's magnetic field is produced by a number of coils.

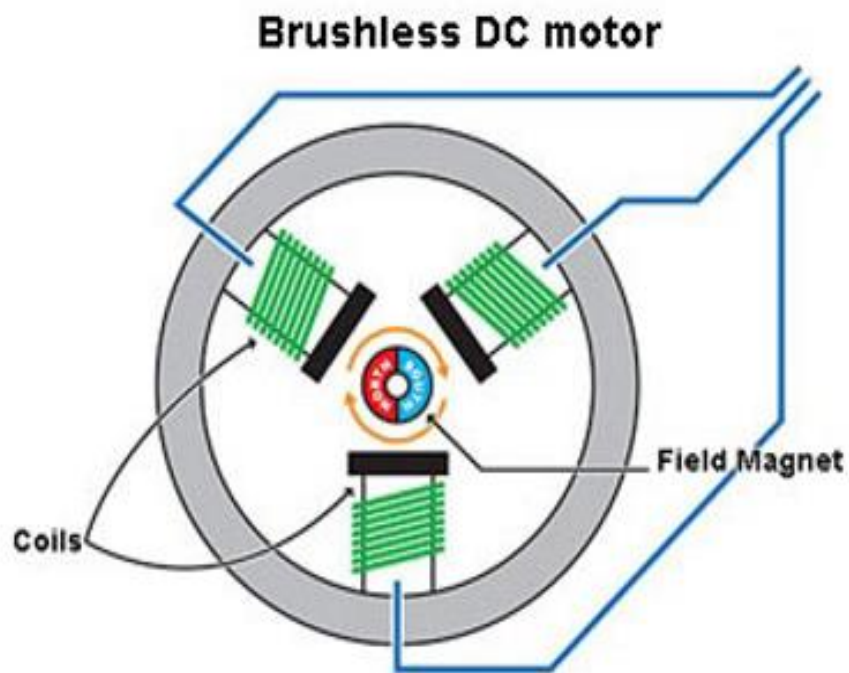


Figure 3.1 Diagram of Three-Phase Brushless DC Motor [6]

Although an induction (asynchronous) motor or switching reluctance motor can also be used in BLDC motor systems, they are frequently constructed similarly to permanent magnet synchronous motors (PMSM). Additionally, they might use axial, neodymium magnets, out runners (where the rotor is outside the stator), or in runners (where the rotor is inside the stator) (the rotor and stator are flat and parallel).

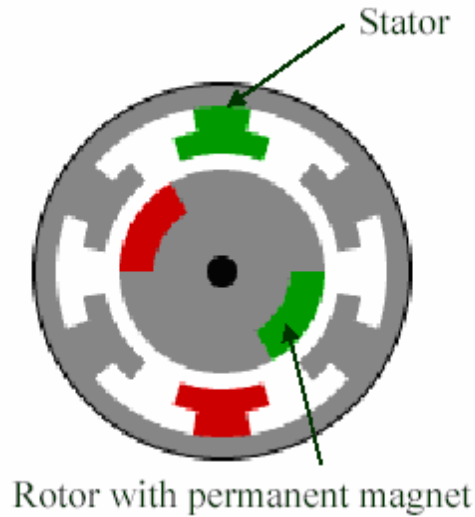


Figure 2.2 cross-section view of a brushless dc motor[2]

The BLDC motor stator is constructed of laminated steel that is stacked up to hold the windings, much like an induction AC motor. A stator's windings can be set up in either a delta arrangement or a star pattern (Y). The primary distinction between the two patterns is that although the Y pattern delivers high torque at low RPM, the pattern does not. The configuration prevents losses, efficiency, and torque degradation by sending half of the voltage across the winding that isn't being driven.

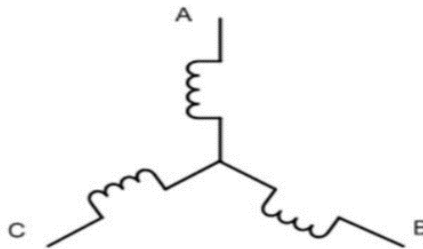


Figure 3.3 Three-Phase BLDC Motor Stator Windings [6]

The total current flowing through all three phases must equal zero since three stator coil windings of the three-phase BLDC motor are connected at the center.

3.2 Mathematical modeling of BLDC Motor

Three-phase windings that are coupled to one another make up the BLDCM. The motor is run in a six-step driven mode with two-phase conduction [35]. The armature reaction and

cogging torque are disregarded under the following presumptions; a square pattern describes the distribution of the air gap magnetic field. Mutual inductance, phase inductance, and all three types of resistance share the same properties[36], If core losses and magnetic circuit saturation are ignored and the transition between the two phases is assumed to be instantaneous.

The BLDCM equation can be expressed mathematically as follows:

$$v_a = Ri_a + L \frac{di_a}{dt} + e_a \quad (3.1)$$

$$v_b = Ri_b + L \frac{di_b}{dt} + e_b \quad (3.2)$$

$$v_c = Ri_c + L \frac{di_c}{dt} + e_c \quad (3.3)$$

Where, v_a, v_b, v_c are the phase voltages, R is the stator winding resistance, L is total phase inductance, i_a, i_b, i_c are the phase currents, and e_a, e_b, e_c are the EMFs with equation:

$$e_a = K_b \omega_n F(\theta_e) \quad (3.4)$$

$$e_b = K_b \omega_n F\left(\theta_e + \frac{4\pi}{3}\right) \quad (3.5)$$

$$e_c = K_b \omega_n F\left(\theta_e + \frac{2\pi}{3}\right) \quad (3.6)$$

Where k_b EMF constant and $F\theta_e$ is function of an angle of electromotive force

$$F(\theta_e) = \begin{cases} 1 & 0 \leq \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi} \left(\theta_e - \frac{2\pi}{3} \right) & \frac{2\pi}{3} \leq \theta_e < \pi \\ -1 & \pi \leq \theta_e < \frac{5\pi}{3} \\ -1 - \frac{6}{\pi} \left(\theta_e - \frac{5\pi}{3} \right) & \frac{5\pi}{3} \leq \theta_e < 2\pi \end{cases} \quad (3.7)$$

The following equation can be used to indicate how much electrical torque of the BLDC motor produces[7][2]

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (3.8)$$

By substituting equation (3.4)-(3.8) to (3.9) the equation for torque is written as follow

$$T_e = K_t \left[F(\theta_e) i_a + F\left(\theta_e + \frac{4\pi}{3}\right) i_b + F\left(\theta_e + \frac{2\pi}{3}\right) i_c \right] \quad (3.9)$$

The following is the mechanical equation for the motor model.

$$J \frac{d\omega_m}{dt} = T_e - T_L \quad (3.10)$$

It is a simplification since the model becomes a two-inertia system by replacing integration because the mechanical equation and coefficient of friction are described in numerous works.

The following equation is used to compute the value of the electrical angle.

$$\frac{d\theta_e}{dt} = n_p \omega_m \quad (3.11)$$

Where n_p a pole is pair and ω_m is mechanical speed of the motor

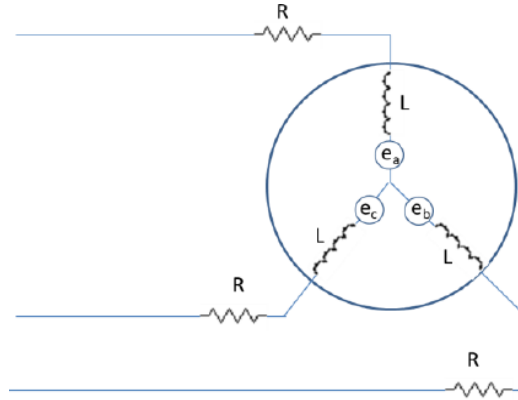


Figure 3.4 Equivalent Circuit of BLDC Motor [38]

3.3 Extended kalman filter estimation

Characteristics of Extended Kalman Filter (EKF) handle nonlinear process and measurement models by resorting to linearization for the propagation of error covariance matrix and Kalman gain computation.

The Extended Kalman Filter (EKF) is an extension of the classic Kalman Filter for non-linear systems where non-linearity are approximated using the first or second order derivative.

The traditional Kalman filter was created exclusively for linear systems. BLDC motors are one example of real-time systems that are not linear. Nonlinearities may be disregard linearizing the non-linearity is one strategy for dealing with the non-linearities that cannot be ig-

nored. The Extended Kalman Filter is a variant of the Kalman filter, is produced by using the Taylor series to account for the nonlinearity of the system equations (EKF).

The Extended Kalman filter design can linearize the nonlinear Gaussian signal model in the event that the most recent state estimations are unimportant[37]. Linearizing the nonlinearity is one strategy for dealing with the non-linearities that cannot be ignored. Applying the Taylor series to the system equations nonlinearity results in the Extended Kalman Filter, version (EKF). The Extended Kalman filter design linearizes the nonlinear Gaussian signal model with respect to the most recent state estimation [14]. The equations for prediction and correction make up the EKF. Using a mathematical model that considers earlier estimates, the states are predicted in the first stage of the calculations, and in the second stage, the predicted states are continuously rectified using a feedback correction mechanism. The weighted difference of the output signals that were measured and calculated is contained in the additional term, which adds a term to the expected states using actual measured states (which are collected in the first step [39]. The following are the primary design processes for a discretized Extended Kalman Filter-based BLDC Motor drive that without a speed and rotor position sensor:

- Choosing a machine model for the time domain
- abstracting the machine model
- calculating the noise and the state covariance Matrix Q, R, and P

Using the equations listed above, a complete BLDC Motor model can be written as a state equation.

$$\frac{d}{dt} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \\ \omega_m(t) \\ \varphi(t) \end{bmatrix} = A \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \\ \omega_m(t) \\ \varphi(t) \end{bmatrix} + B \begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \\ T_l \end{bmatrix} \quad (3.12)$$

$$\begin{bmatrix} \dot{i}_a(t) \\ \dot{i}_b(t) \\ \dot{i}_c(t) \end{bmatrix} = C \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \\ \omega_m(t) \\ \varphi(t) \end{bmatrix} + D \begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \\ T_L \end{bmatrix} \quad (3.13)$$

Here input and output matrices are provided:

$$A = \begin{bmatrix} -\frac{R}{L} & 0 & 0 & -\frac{K_b}{L}F(\theta_e) & 0 \\ 0 & -\frac{R}{L} & 0 & -\frac{k_b}{L}F(\theta_e + \frac{4\pi}{3}) & 0 \\ 0 & 0 & \frac{R}{L} & -\frac{k_b}{L}F(\theta_e + \frac{2\pi}{3}) & 0 \\ \frac{K_b}{J}F(\theta_e) & \frac{k_b}{J}F(\theta_e + \frac{4\pi}{3}) & \frac{k_b}{J}F(\theta_e + \frac{2\pi}{3}) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & pole & 0 \end{bmatrix} \quad (3.14)$$

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \frac{1}{L} & \frac{1}{L} & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & \frac{-1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (3.15)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (3.16)$$

Feed forward matrix (i.e. D) is full of zeroes in the BLDC Motor

An Algorithm of extended kalman filter is written in the following steps

Step 1: The system is represented in state space as follows.

$$\frac{dx}{dt} = Ax + Bu \quad (3.16)$$

$$Y = Cx \quad (3.17)$$

Step2: time-discreet state-space model[43]

$$X(k+1) = Ad * X(k) + Bd * U(k) \quad (3.18)$$

$$Y(k) = Cd(k) * x(k) \quad (3.19)$$

Step3: Creating the covariance matrices from scratch Use of accurate initial values for the various covariance matrices[41] Q, R, and P is a crucial component of the design of EKF. The model error, system delays, and noise from the voltage measurements are all accounted for by the system noise covariance Q. Measurement noise introduced by the current sensor is taken into account by the noise covariance R.

The values of parameters' are chosen by trial and error.

After some trial runs, it was found that the following set of parameters allows EKF-WGI (Weighted Global Iteration) to reach a solution that matches the calculated and measured measurement quantities[27]

$Q = q.I$ with $q = 2 \times 10^{-6}$ MPa, essentially a very small number;

$R = \delta.I$ with $\delta = 10$ MPa, to represent the accuracy in modulus measurement

$P = p.I$ with $p = 0.8$ MPa²; and $w = 2$

$$Q = 0.02I \quad (3.20)$$

$$P = 0.1I \quad (3.21)$$

$$R = 0.1I \quad (3.22)$$

Step4: the state vector's initialization

$$X_0 = x(t_0) \quad (3.23)$$

step5: Prediction of the state vector[43]. Prediction of the state vector at sampling time $(k+1)$ from the input vector $u(k)$ and the state vector at previous sampling time $X(k)$, by using $Ad(k)$ and $Bd(k)$, is obtained[43] by performing,

$$X(k+1) = Ad(k)x(k) + Bd(k)U(k) \quad (3.24)$$

Based on measurements up to the k^{th} instant, $X(k+1)$ reflects the expected value at the $(k+1)$ the moment.

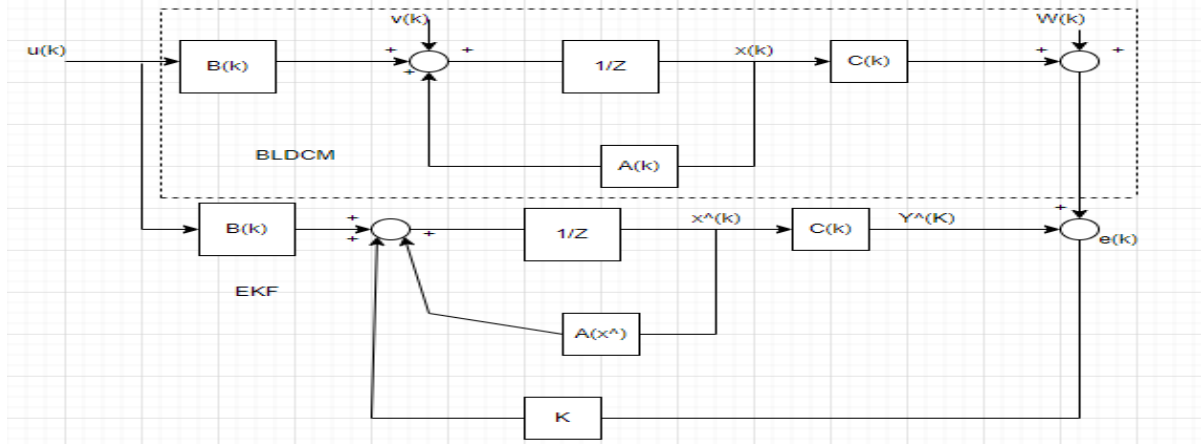


Figure 3.5 Structure of EKF[14]

Step6 Prediction covariance estimation the prediction covariance matrix is calculated as

$$P^*(k+1) = f(k+1) * p^{\wedge}(k) * f^T(k+1) + Q \quad (3.25)$$

The gradient matrix f is present system process matrix[43]

$$F(k+1) = \frac{\partial}{\partial x} [A dx + B du]_{x = x^{\wedge}(k+1)} \quad (3.26)$$

Step7 The correction matrices used to calculate the gain of the Kalman filter are

$$K(k+1) = \text{Inv}(p^*(k+1)h^T(k+1)[h(k+1)p^*(k+1)p^*(k+1)h^T(k+1)+R]) \quad (3.27)$$

$H(k+1)$ is the gradient matrix measurement[43], which is defined as

$$H(k+1) = \frac{\partial}{\partial x} [C dx]_{x = x^*(k=1)} \quad (3.28)$$

Step 8: Estimating the state vector State vector estimation is carried out as follows: correction of state vector estimate, filtering at time $(k+1)$,

$$X^{\wedge}(k+) = x^*(k+) + k(k+1)[y(k+1)-Y^{\wedge}(k+1)] \quad (3.29)$$

$$Y^{(K+1)} = Cdx^{(k+1)} \quad (3.30)$$

Step 9: Matrix of estimate error covariance the mistake you may get the covariance matrix from:

$$P^{(k+1)} = p^{(k+1)} - k(k+1)h(k+1)p^{(k+1)} \quad (3.31)$$

Step 10

$$K = k + 1 \quad (32)$$

$$X(k+1) = x(k-1)p(k) = p(k-1) \text{ and go to step 1} \quad (3.33)$$

Where $k+1$ is sampling time

CHAPTER FOUR

CONTROLLER DESIGN

4.1 Introduction

Fuzzy logic is used in a number of controllers because it does not require an accurate model of the system to be controlled. Fuzzy logic works by executing rules that correlate the controller inputs with the desired outputs.

Fuzzy logic controller is one of the modern controller that used to control sophisticated control system [2]. Complex requirements can be implemented with its help in very easy-to-make, low-cost controllers. Fuzzy logic applications have grown rapidly in number and variety during the last few years, in addition to ordinary consumer goods like cameras, camcorders, washing machines, and microwave ovens. Applications include industrial process control, medical instruments, and decision support systems. Even though many decision-making and problem-solving tasks are too complex to be defined quantitatively, people frequently succeed by using knowledge that is approximate rather than exact. Fuzzy logic focuses on the relative value of accuracy. The term "fuzzy logic" has two distinct meanings. In more limited terms fuzzy logic is a multi-valued logic-based logical system. But in a broader sense, the theory of fuzzy sets and fuzzy logic are interchangeable terms.

Selection criteria for Fuzzy logic controllers

- ✓ Fuzzy logic controllers are a useful tool for modeling nonlinear systems.
- ✓ Usually, the conventional control system's design is built on a mathematical model of the plant. It is possible to evaluate a precise mathematical model if it is given with well-known parameters.
- ✓ These characteristics describe an adaptive fuzzy logic controller; an adaptable characteristic allows a system to function consistently even while its load and uncertainty factors are changing.

4.2 Fuzzy logic Controller design

The fuzzy logic controller and reference current controller in the control system use the signals created to adjust the BLDC motor current to the reference current value generated by the speed controller, as shown in Fig. 4.1 below. Figure 4.1 depicts the basic layout of a fuzzy logic controller. The fuzzy controller, defuzzification, fuzzy rule-base, fuzzy inference engine, and fuzzification are made up of the following four elements.

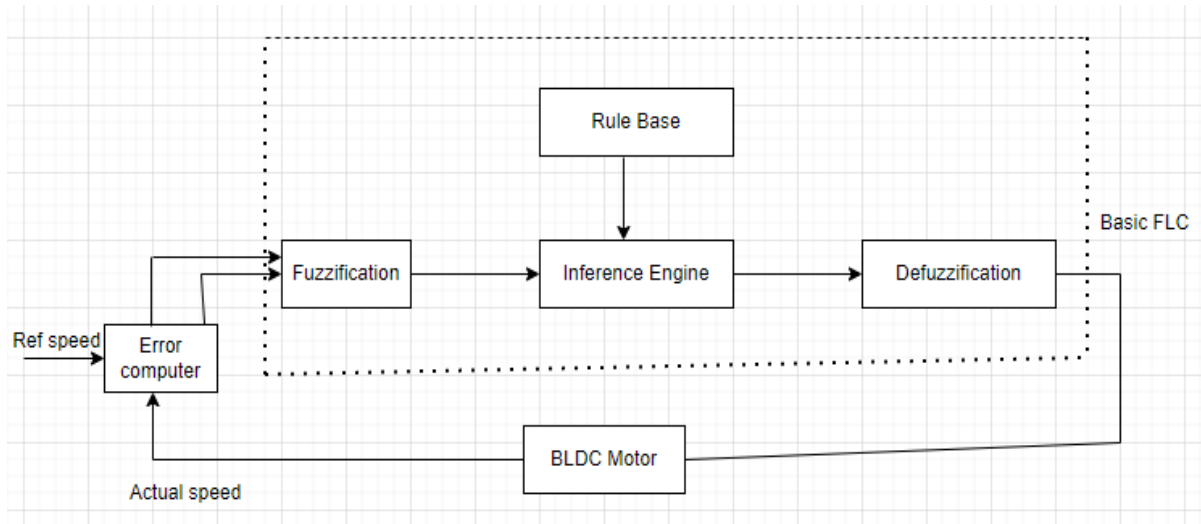


Figure 4.1 Basic Design of BLDC Motor with Fuzzy Logic Controller

Fuzzification: Fuzzification is the process of decomposing a system input and/or output into one or more fuzzy sets. Many types of curves and tables can be used, but triangular or trapezoidal-shaped membership functions are the most common, since they are easier to represent in embedded controllers.

Inference Engine: An inference engine is a tool used to make logical deductions about knowledge assets

Defuzzification: Defuzzification is the process of obtaining a single number from the output of the aggregated fuzzy set. It is used to transfer fuzzy inference results into a crisp output. In other words, defuzzification is realized by a decision-making algorithm that selects the best crisp value based on a fuzzy set.

The output of a fuzzy logic controller is PW, and its inputs are speed (e) and change in speed (Ce)[2]. Error is defined as the difference between the reference speed and the actual speed. The difference between the output and both the prior and present errors is referred to as

"change in error." The prior PWM is multiplied by the PWM change, which may be positive or negative, to get the new PWM. Fuzzy logic uses language variables as opposed to numerical variables. A verbal variable is created by "fuzzing" a numerical variable. The most common way to represent fuzzy logic in words is to use logical conclusions, like IF-THEN rules. These guidelines describe a set of figures called fuzzy membership functions [2][28].

In contrast to mathematical computations, fuzzy logic stated operational laws using verbal phrases. Many systems are too complex, even with sophisticated mathematical formulae, to adequately model making it unfeasible to employ standard approaches in these systems. However, the linguistic principles of fuzzy logics can be used to specify the operational properties of such a system. Multiple linguist levels are used to express the inputs to the fuzzy controller; those are Negative big, Negative medium, Negative small,

These levels can be classified as Zero, Positive small, Positive medium and Positive big. The speed loop error signal's pattern, which the fuzzy controller monitors, and the change in the error are its two input signals. The command speed $_ref$ is therefore matched by the real speed $_m$. Since CE is equivalent to $dE/dt = E/t = CE/T$ s, it is equal to the E throughout the sample period T s. To dE/dt , CE is connected. The table 4.1 blow contains the 49 fuzzy logic controller rules

Table 4.1 7x7 fuzzy rule based table

CE/E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The Fuzzy model

The fuzzy model was developed in the fuzzy logic toolbox of MATLAB software (Math works, 20211) using the Mamdani minimum-maximum inference engine.

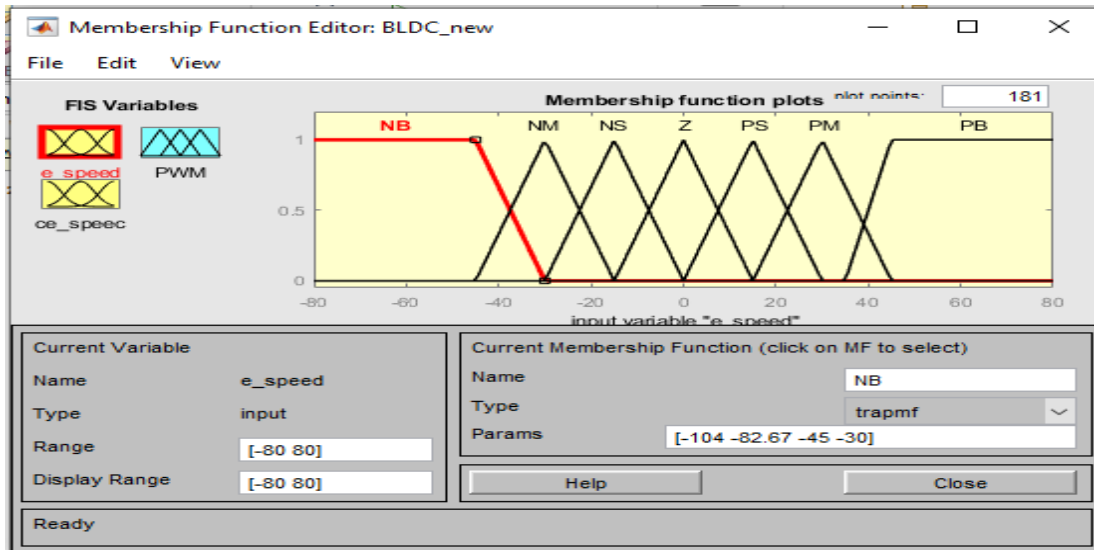


Figure 4.2 Input one of fuzzy membership function (speed)

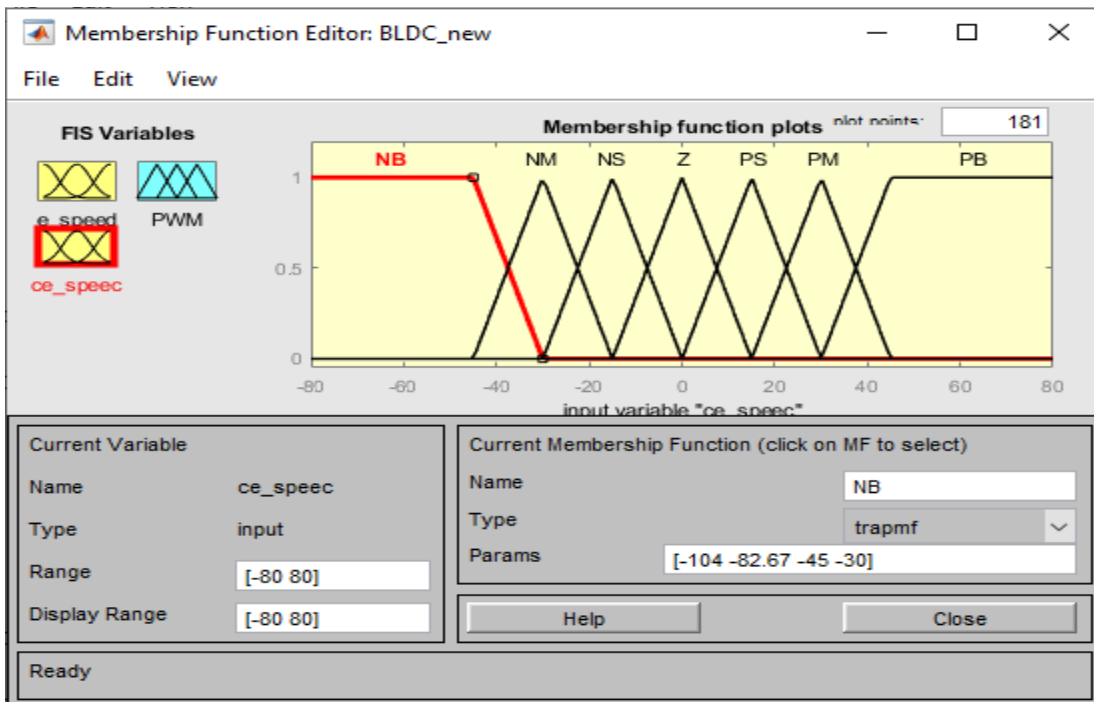


Figure 4.3 Input two changes in speed (c-speed)

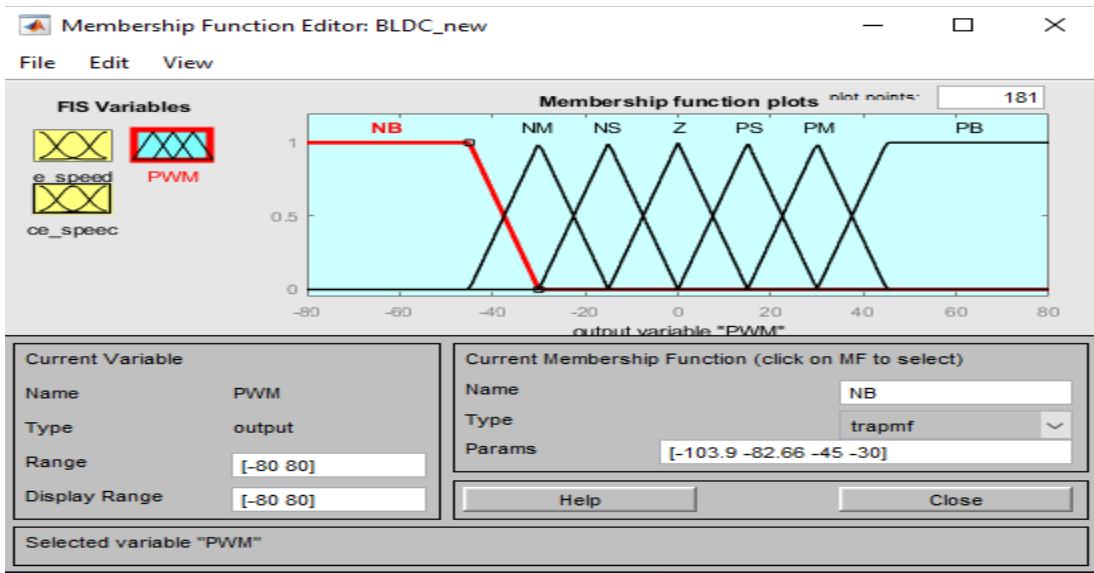


Figure 4.4 Fuzzy output (PWM)

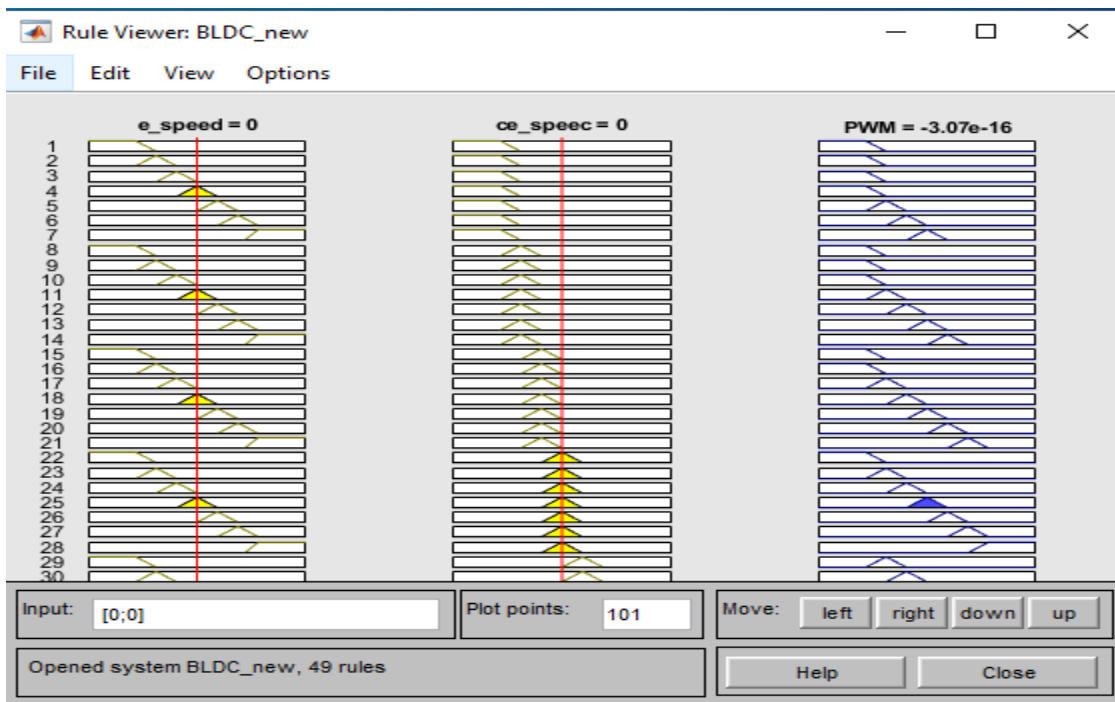


Figure 4.5 Fuzzy rule views

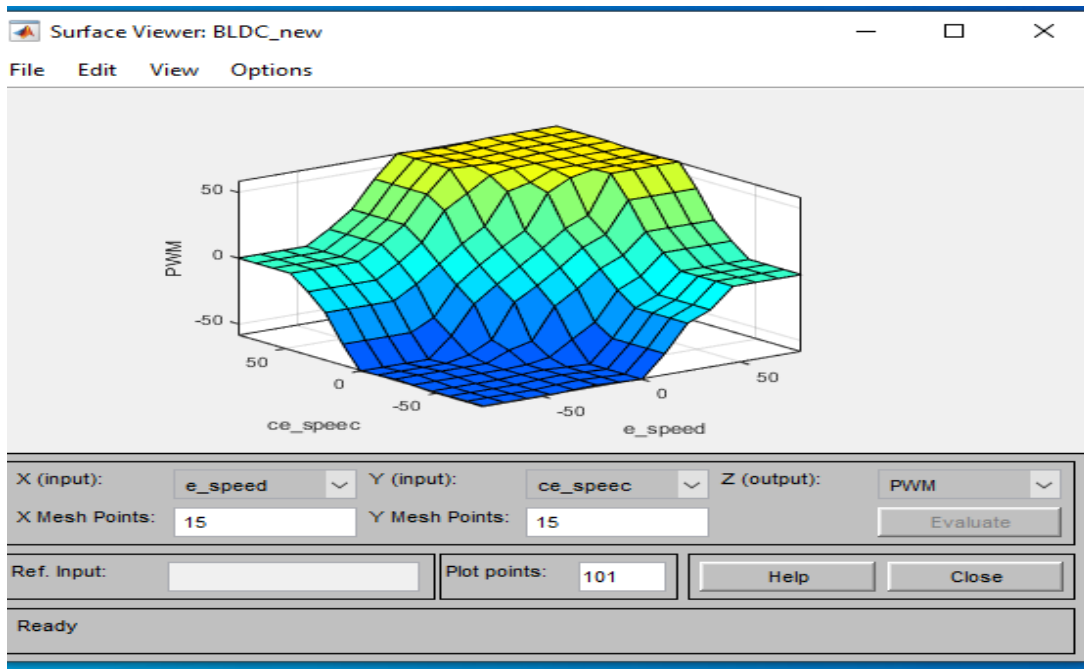


Figure 4.6 Surface viewers

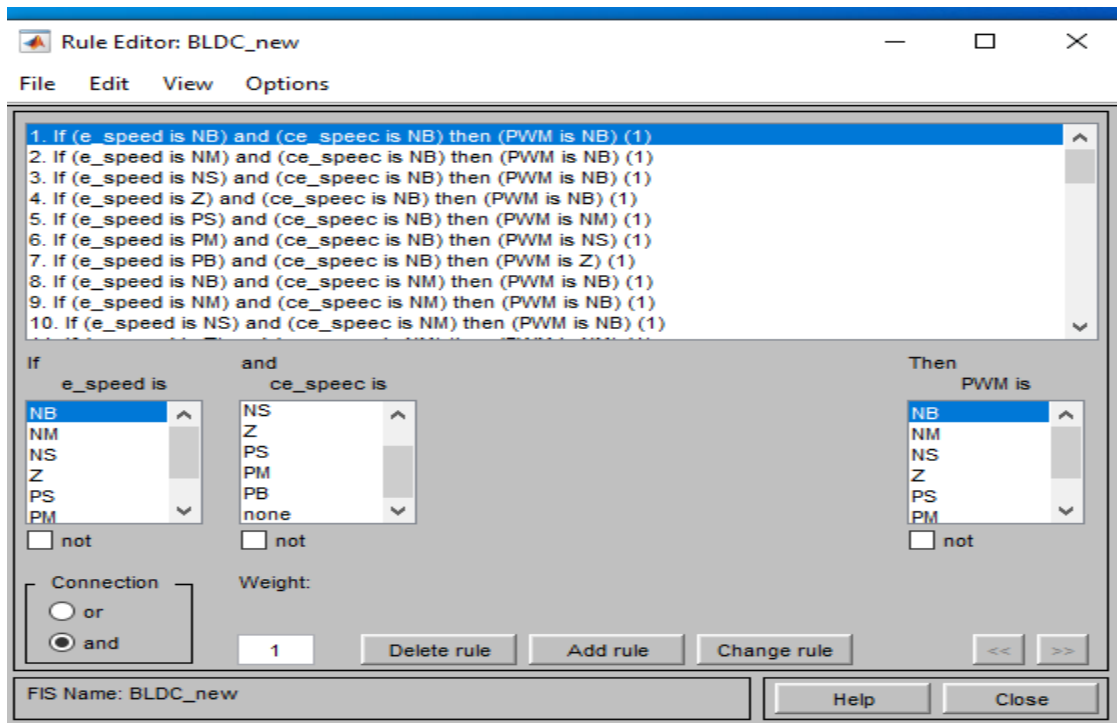


Figure 4.7 Fuzzy editors BLDC-new

4.3 Hysteresis current controller

Hysteresis current control has desirable characteristics such as high stability, fast and accurate dynamic behavior. On the other hand, conventional hysteresis method includes some undesirable results, such as variable switching frequency that causes audio noises, high switching losses and injection of high-frequency current components to the source current that makes it difficult to design suitable filters to remove these high-frequency harmonics. Many switching methods are used to produce switching pulse which leads to generate reference current. Hysteresis current control (HCC) has been noticed more than other current control techniques, due to simplicity and quicker dynamic response[10]

Hysteresis current control is used for generating the switching pulses. Among the various current control techniques, HCC is the most extensively used technique because of the non-complex implementation, outstanding stability, absence of any tracking error, very fast transient response, inherent limited maximum current, and intrinsic robustness to load parameters variations.[10]. The drawback of this method is that the switching frequency does not remain constant but varies along different portions of the desired current[44].

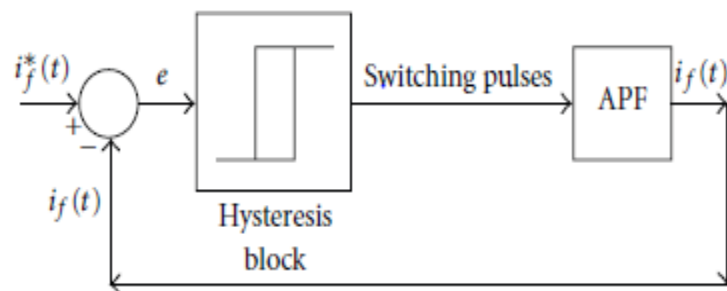


Figure 4.8 Hysteresis current control loop[44]

The current controller design to perform this work is taken from MATLAB /Simulink Simscape model.

Current Control Block

In PWM current control block, the reference phase currents ($i_a \text{ ref}$, $i_b \text{ ref}$, $i_c \text{ ref}$) are compared with the motor's actual phase currents (i_a , i_b , i_c). As shown in Figure 4.9, the hysteresis

current control is performed in the function block $fa(s)$ by using the measured phase current i_a , the reference current I_{max} , and the rotor position θ .

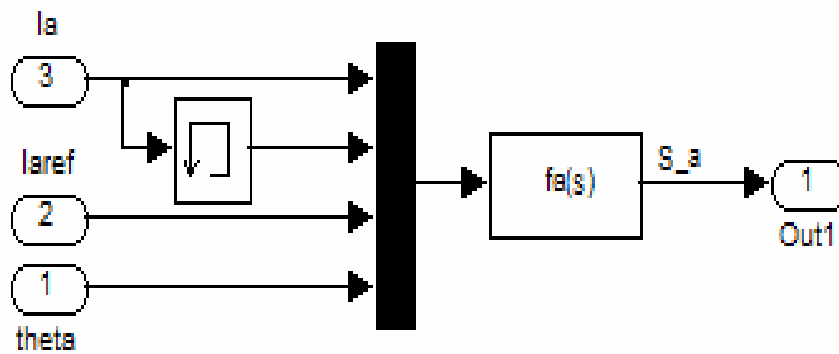


Figure 4.9 Current Control Block[16]

PI Controller is tuned automatically tuned by using Ziegler formula in MATLAB Tool box for the performance comparison of proposed fuzzy logic controller

Table 5.1 Parts of overall design system

Parts of overall design system	Definition
The speed control block	The FLC used for speed control based on the error generated from the reference and estimated speed
The inverter block	convert DC to pulsed AC
Hysteresis current control block	For controlling the current and feed control signal for the gate (PWM).
Commutation logic block	By switching on and off used for appropriate AC current generation.
Voltage and current transformation block	Transform three phase AC to two phased DC (park and Clark transformation)
Speed estimation block	used to estimate the speed of motor

5.2. Simulation Model

Under various speed commands, the suggested speed estimate technique is studied in the preceding chapter; the extended kalman filter state estimator technique-based fuzzy logic speed controller architecture was given. Simulations of the speed controller and estimators for different loads no load, full load, no and with and without external disturbances.

Based on MATLAB 2021a, a program that simulates dynamic system models based on actual physical systems, the simulation model in use. The model makes it simple to model PMDC motors based on trapezoidal back EMF and makes it simple to adjust motor parameters while providing an overview of all system signals. A MATLAB/ Simulink model of BLDC motor drive was designed using components from the Power System Block collection. This Simulink add-on is incredibly helpful because it offers models for many different power electron-

ics components and control systems. The setup of the BLDC motor, park transforms, and crack transforms is taken from an already-existing Simulink file. Figure 4.1 shows how the theory described in Chapter 4 of this thesis was used to create the fuzzy logic speed control and the speed estimation structure. Table 5.1 provides a list of the three phases, two kilowatt, rated speed, and motor parameters for the BLDC motor used in this thesis.

The model shown above in Figure 5.1 is an overview of the designed system depicting the major subcomponents of the system.

Table 5.2 parameters used in BLDCM Sims cape model and control

Rated Speed [RPM]	3000
Rated Torque [Nm]	0.5
Torque Constant K_t [kgm/A]	3.36×10^{-2}
Back EMF Constant K_b [V/kRPM]	26.00
Line to Line Resistance R [Ohm]	11.00
Line to Line Inductance L [mH]	33.50
Rotor Inertia I_r [kgm ²]	2.3×10^{-5}
Number of poles	4

5.3. Results

The result of extended kalman filter based sensor-less estimation is used to evaluate the performance of the motor. For this simulation, understanding the motor's parameter is crucial, the variation in the parameter's effect was investigated based on different should be equivalent, as indicated in Figure 5.2, for proper rotational flux generation, conditions that are set on their effect on the robustness of the speed controller because the estimator is very parameter sensitive. The first simulation result for sensor-less speed control of BLDC motors using extended Kalman filters is the three phase stator current produced by the three phase voltage source inverter. Using hysteresis current control blocks, this three-phase voltage source inverter regulates the generation of the appropriate stator current. The phase shift between the three phases' currents should be 120 degrees, and their amplitudes.

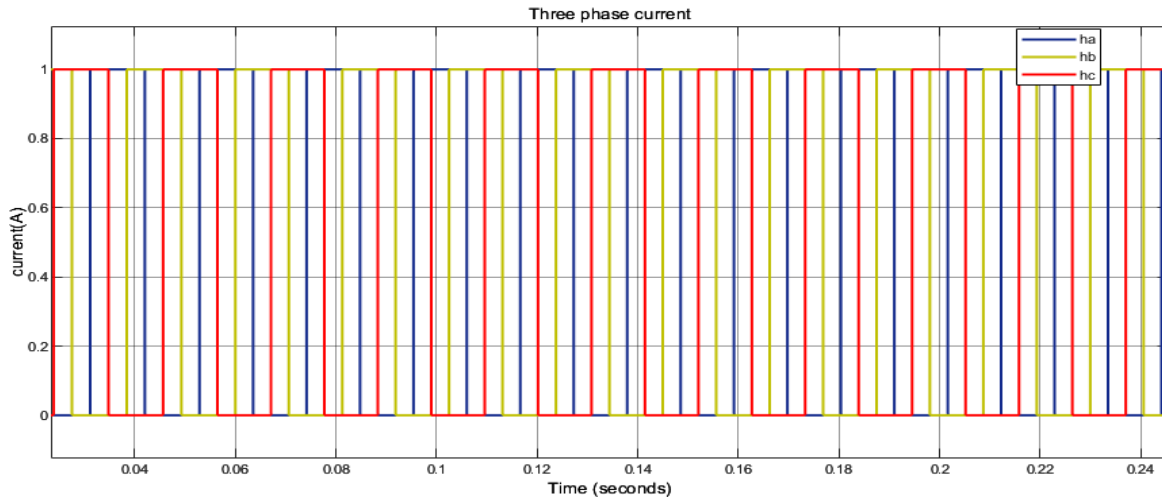


Figure 5.2 Three phase stator current at 150rad/s

5.3.1. Set point tracking capability

Knowing how well an estimator performs based on its capacity to get the real value closer to the reference value, particularly during transient responses, is essential. This criterion has received widespread acceptance as the key performance indicator for speed estimation. The suggested estimator follows the step input under load conditions, as seen in Figure 5.3, With a settling time of less than 0.01 seconds and a maximum steady state inaccuracy of 0.007%, this shows how changing the system's reference with significant transient performance may be tested. The tracking performance of the real to the reference speed is good.

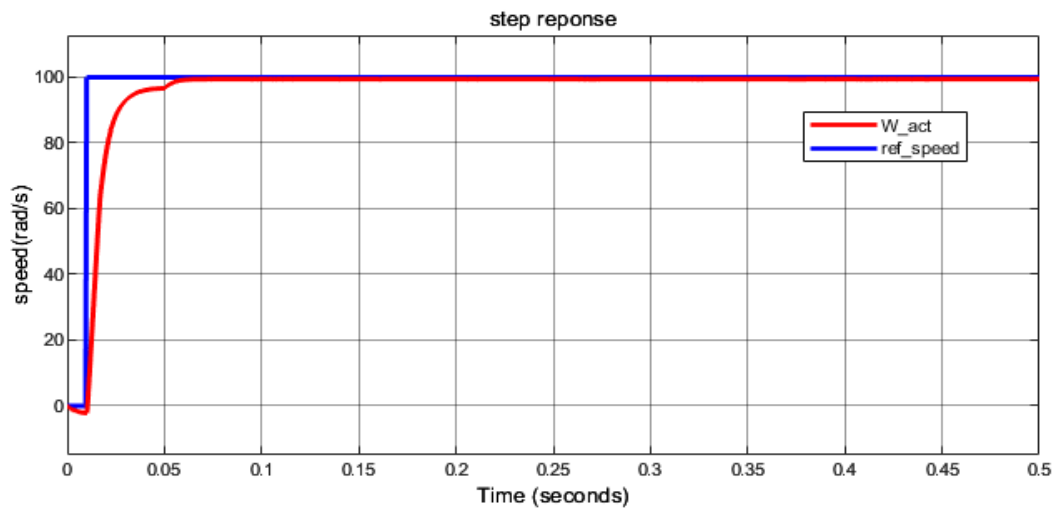


Figure 5.3 Speed response for step reference input (100rad/s) with 2Nm load torque

Figure 5.4, which depicts variable speed driving of a BLDC motor with variable step speed

response, shows real speed tracking reference speed at intervals of 0.01 seconds, for 0.011 seconds, the actual speed tracks the reference as the input varies step size to test the input's ability to track different input. The fuzzy logic control was put to the test while a load disturbance was present. In the simulation shown in figure 5.4, a step change of 0.1Nm at a speed change of 0.1s results in a good speed control response. Thus, the speed controller's design produces a good ability to reject disturbances.

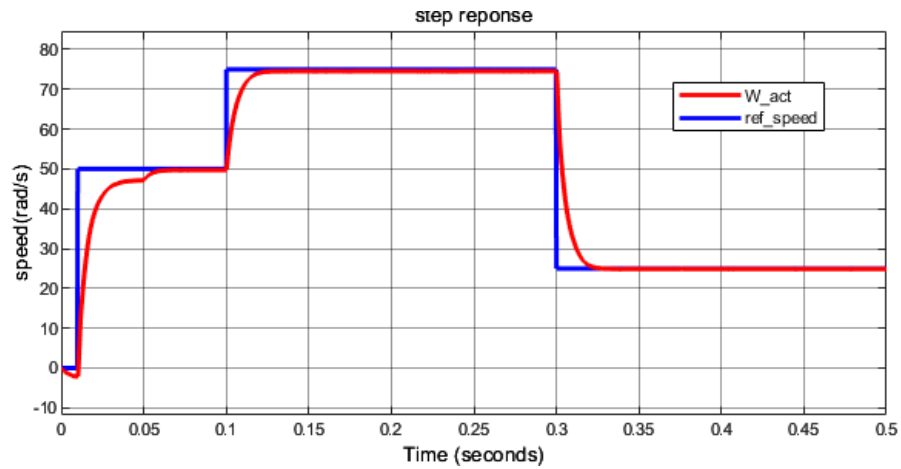


Figure 5.4 Speed responses for variable input with 2Nm load torque

The brushless direct current motor (PMSM), which is trapezoidal in shape, is seen in Figure 5.5.

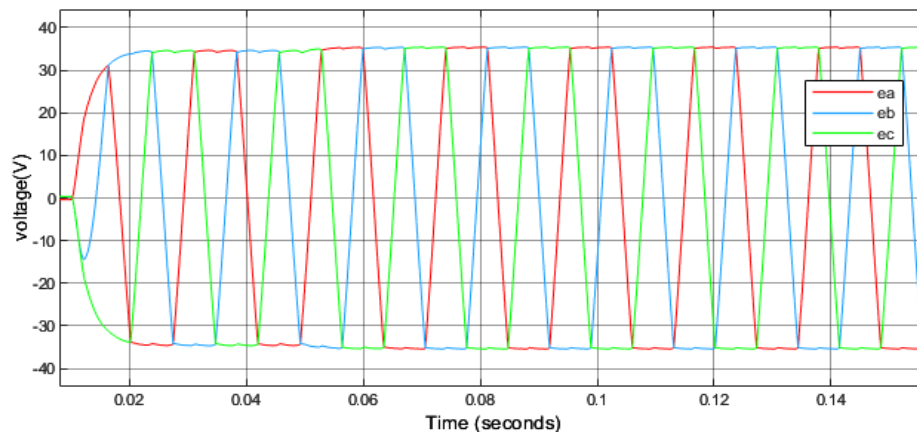


Figure 5.5 Trapezoidal induced EMF functions in brushless DC motor

Actual angle as shown in Figure 5.6, theta is generated with a bound output of minus $-\pi$ to π . The fitting angle is created to control the motor's position and shows how closely actual and reference speeds match each other.

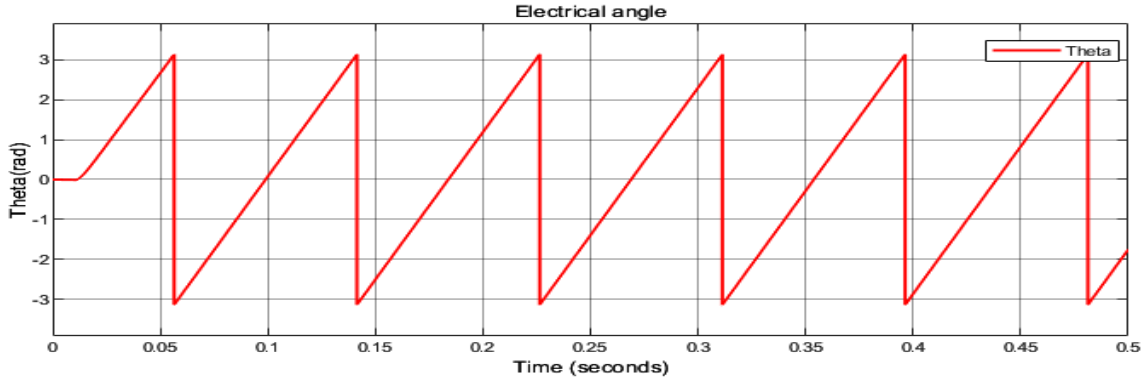


Figure 5.6 the electrical rotor angle in degree

5.3.2 Torque response quickness

When the motor starts, a 0.5 Nm load torque is provided; after 0.05 seconds, this value is increased to 1.5 Nm, which causes a decrease in motor speed. This is the outcome of a torque mismatch, which occurs when the produced torque is less than the torque of the load. As shown in Figure 5.7, the controller increases the developed to account for this difference; as a result, the motor speed increases and the position is returned to its initial setting.

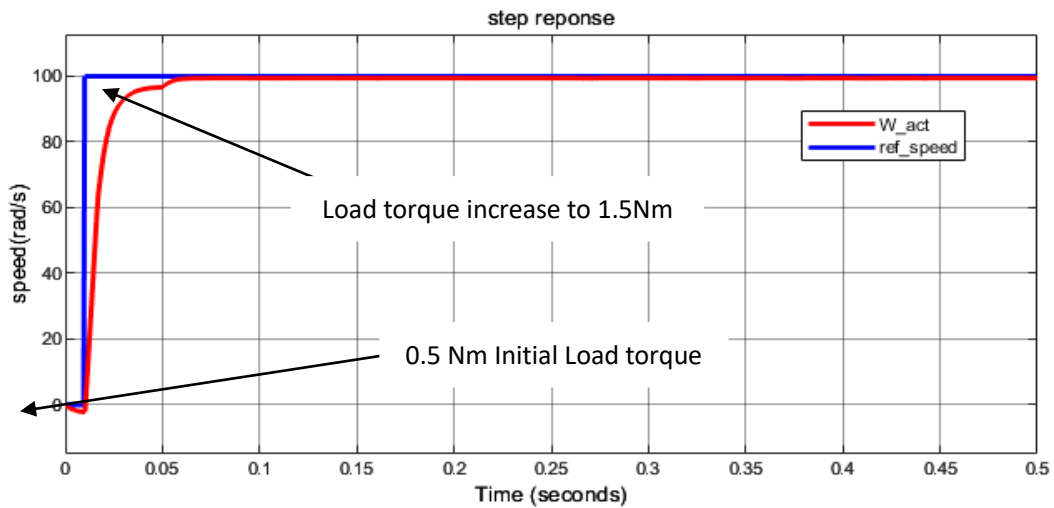


Figure 5.7 Load torque effect on proposed system.

5.3.3 Behavior of low speed

This test is intended to assess the speed estimator's performance at low speeds. Figure 5.8 demonstrates that, with a steady state inaccuracy of 0.02rad/s and a significant transient performance rise time of less than 0.01 seconds, the estimated speed closely matches the actual speed and the reference speed.

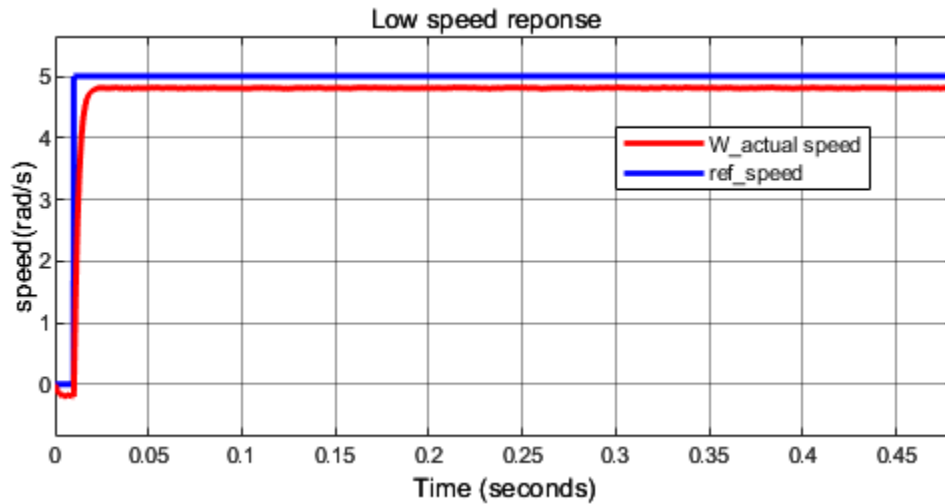


Figure 5.8 Speed responses for 5rad/s with 1.5Nm load torque

Using the same parameters in the BLDC motor and the extended Kalman filter speed estimator, the tracking performance of the estimator is shown in Figure 5.9, the proposed estimator tracks both the step signals reference input. This shows the tracking performance of the estimator and actual speed to the reference speed can be examined by changing the reference of the system with the maximum steady state error of 0.037% and good transient performance with rise time less than 0.06 second. It is important to know the performance of an estimator based on the ability of the estimated speed to converge the actual value, especially during the transient response. This criterion has been well accepted as a primary indicator when benchmarking the performance of a sensor-less speed estimator. It shows the convergence of the estimated rotor speed to the actual speed.

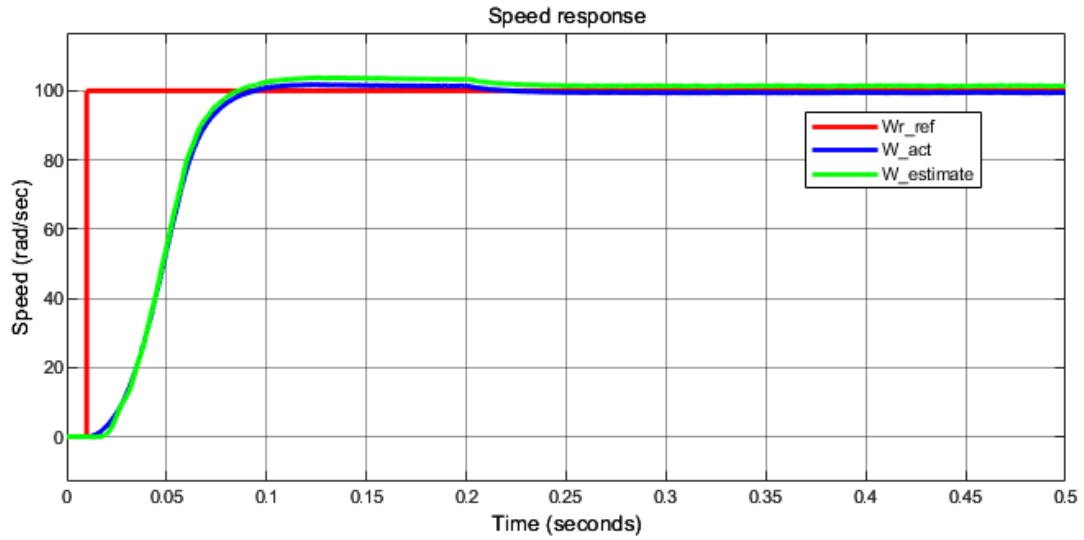


Figure 5.9 Tracking performance of the estimator

5.3.4 Speed response using Proportional Integral (PI) Controller

As shown in Figure 5.10, the proposed estimator with PI controller track the step signals reference input. This shows the tracking performance of the actual speed to the reference speed can be examined with the maximum steady state error of 3% and maximum overshoot of 10.1% performance with rise time less than 0.1 second. As compared to the Fuzzy logic controller the transient and steady state performance is no good.

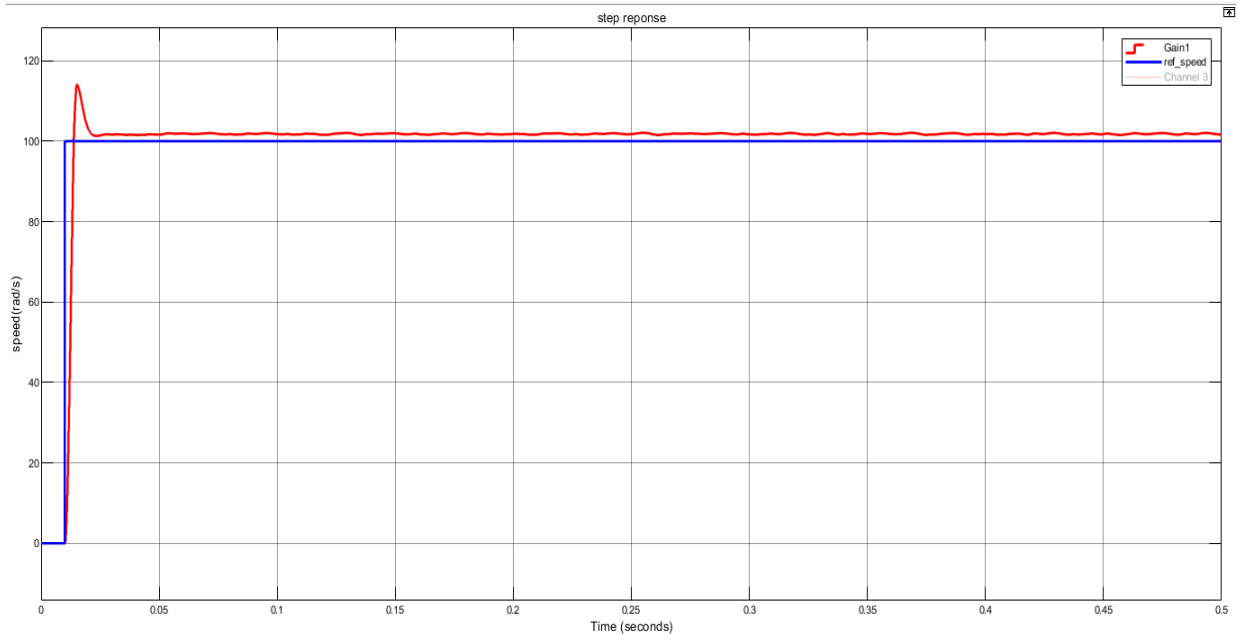


Figure5.10 Speed response using Proportional Integral (PI) Controller

5.3.5 Performance comparison of proposed controller (FLC) with PI controller.

Table 5.3 Performance comparison of FLC and PIC

Comparison parameters	FLC controller	PI controller
Overshoot	0	10.1%
Stead state error	0.007%	3%
Settling time	0.01	0.1
Rise time	0.1	0.1

As we have seen from the Table 5.3 the values of steady state error, settling and overshoot of PI controller is high. Therefore the performance of fuzzy logic controller is good rather than PI controller.

5.3.6 Performance of proposed estimator (EKF)

Tracking performance of the estimator is shown in Figure 5.9, the proposed estimator tracks both the step signals reference input. This shows the tracking performance of the estimator and actual speed to the reference speed can be examined by changing the reference of the system with the maximum steady state error of 0.037% and good transient performance with rise time less than 0.06 second. It is important to know the performance of an estimator based on the ability of the estimated speed to converge the actual value, especially during the transient response. The performance of estimator is good as we seen from the figure 5.9

CHAPTER SIX

CONCLUSION AND RECOMMEDATION

6.1 Conclusion

The extended kalman filter is developed in this thesis in order to increase the possibility of sensor less BLDC motor speed estimation.

With adequate accuracy in the operation dynamic and steady state models, since the precise estimation of rotor speed is one of the many advantages and applications of the extended kalman filter. It is used in this study. The fuzzy logic control was put to the test while a load disturbance was present.

The outcome showed a satisfactory speed control reaction during a 0.1Nm disturbance at a 0.1s step change. Thus, the speed controller's design produces a good ability to reject disturbances. The suggested estimator follows the step input when under load. This indicates that by changing the system's reference speed, with robust transient performance, a settling time of under 0.01 seconds, and a maximum steady state inaccuracy of 0.007%, the tracking performance of the actual to the reference speed may be evaluated. As demonstrated by the results, it is entirely feasible to estimate the speed and position of sensor-less BLDC motors using an extended kalman filter.

6.2 Recommendation

It is thought that there are many potential topics for additional research studies in this thesis work. Here are a few potential directions.

- Extended kalman filter cannot estimate in higher order derivatives, so that unscented kalman filter is recommended to estimate parameters in higher order derivatives.
- For high and precise motor use, sensor-less vector control may be necessary.
- The system performance can be enhanced by applying the intelligent estimation and control technique.

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APPENDIX

Appendix A-MATLAB code used in the paper

Extended Kalman filter based estimated speed m-file code

```

Function [X_new, Ys, P_new, w] = fcn(U,Y, X,P)
%motor constants
Lm = 0.0193939;
Lr = 0.216423;
Ls = 0.216423;
Rs= 11.05;
Rr = 6.11;
% Rs=0.7;
% Rr=0.65;
%user defined working variables
T=15e-5;
% sigma=0.05;
Sigma=1-(Lm^2/Ls*Lr);
Lsp= (Lm^2)*Rr + (Lr^2)*Rs;
dn=sigma*Ls*(Ls^2); %T*s variable
pp =2;
%for 5*5 we need to define w from the existing variable
w=X(5,1);
%Discretized A
A=[1-(T*Lsp/dn)  0          T*Lm*Rr/dn          w*T*Lm/(sigma*Ls*Ls)  0;
    0          1-(T*Lsp/dn)  -w*T*Lm/(sigma*Ls*Ls)  T*Lm*Rr/dn          0;
    T*Lm*Rr/Lr  0          1-(T*Rr/Lr)          -T*w          0;
    0          T*Lm*Rr/Lr  T*w          1-(T*Rr/Lr)          0;
    0          0          0          0          1];
%Discretized B
B = [T/(sigma*Ls)  0;
     0          T/(sigma*Ls);
     0          0;
     0          0;
     0          0];
C= [1 0 0 0 0;
    0 1 0 0 0];
Q = [ 1  0 0 0 0;
     0  1 0 0 0;
     0  0 1 0 0;
     0  0 0 1 0;
     0  0 0 0 1];
R =[1 0 0 1];
%H is the gradient matrix (Jacobean) of the output function
H= [1 0 0 0 0;
    0 1 0 0 0];
X_mid = A*X + B*U; %for 5x5 this variable is X_mid
Ys = C*X_mid;
w_mid = X_mid(5,1);
phi_dr = X_mid(3,1);
phi_qr = X_mid(4,1);
%F is the gradient matrix(Jacobean) of the state matrix or state function
F =[1-(T*Lsp/dn)  0          T*Lm*Rr/dn          w_mid*T*Lm/(sigma*Ls*Ls)

```

```

T*Lm*phi_qr/(sigma*Ls*Ls);
    0      1-(T*Lsp/dn)  -w_mid*T*Lm/(sigma*Ls*Ls)  T*Lm*Rr/(dn)      -
T*Lm*phi_dr/(sigma*Ls*Ls);
    T*Lm*Rr/Lr      0      1-(T*Rr/Lr)      -T*w_mid      -
phi_qr*T;
    0      T*Lm*Rr/Lr      T*w_mid      1-(T*Rr/Lr)
phi_dr*T;
    0      0      0      0
1];
P_mid = F*P*F' + Q; % Covariance mtrix of prediction
K = P_mid*H'*(inv(H*P_mid*H' + R)); %Kalmans Gain
P_new = P_mid - K*H*P; %Updating of the covariance matrix
X_new = X_mid + K*(Y-Ys); %Here Y is the actual measured value obtained and Ys is
the calculated value from filter
w = X_new (5,1)/pp;% estimated speed

```

Appendix B-MATLAB simulation model block

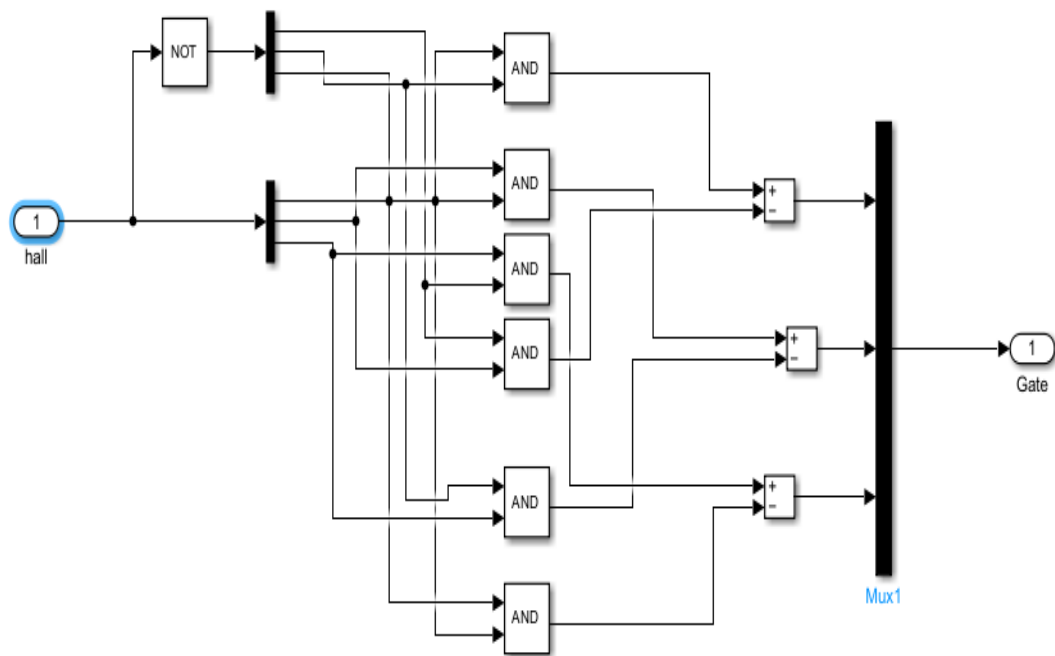


Fig1 of BLDC motor hall effect sensor communication logic

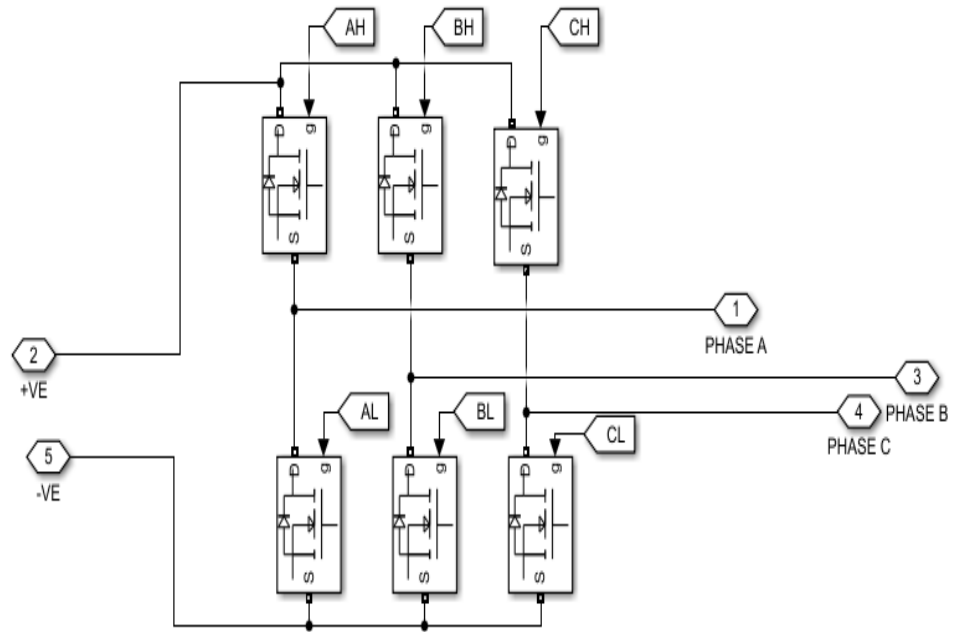


Fig 2 two-level three-phase voltage source inverte

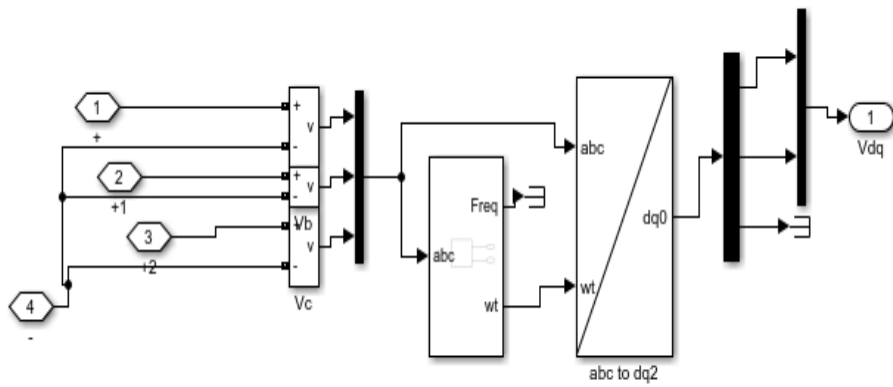


Fig3 of voltage transformation

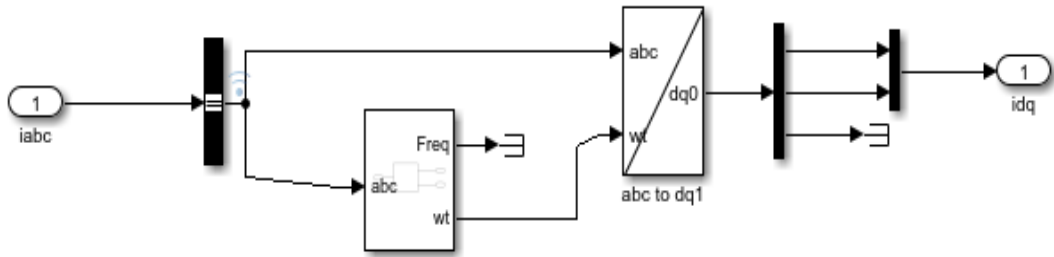


Fig 4 current transformation

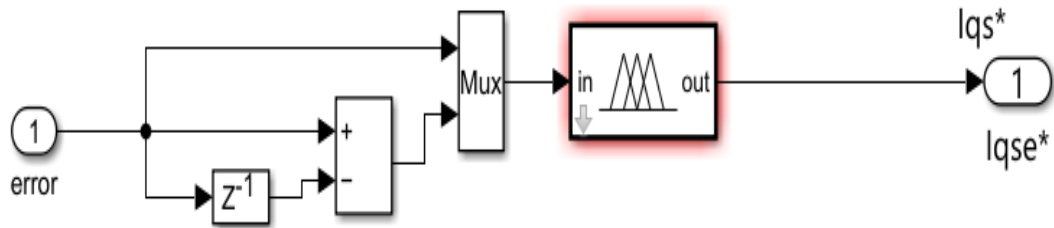


Fig5 speed controller