Sensorless Speed Control of Brushless DC Motor using Sliding Mode Observer

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By

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Abstract

This thesis discusses the speed control method for Brushless DC (BLDC) motor using sensorless technique. The sensorless technique has improved the performance and reliability and reduced the limitations of BLDC motor by eliminating the conventional sensor control methods. The sensorless method used in this paper is Sliding mode observer (SMO), which is an advance technique to control the speed of Brushless DC motor. Sliding mode observer provides a mathematical model of BLDC motor and that model is simulated in MATLAB (SIMULINK) environment to control the speed of Brushless DC motor. The SMO estimates the phase to phase trapezoidal back-EMF by using the stator current and voltages which leads towards the measurement of six rotor positions of the BLDC motor. The mathematical relation between rotor speed and back-EMF is presented to estimate the speed of the BLDC motor. The main contribution of this work is that the chattering problem of SMO is reduced greatly by using some novel idea of smoothing the sign function.

Chapter 1

1. Introduction

1.1 Motivation

Motors have a wide range of usage and in USA nearly 65% of the total power generated is consumed by electric motors [9] and with this fact the worth and importance of a motor can be understood. The key application areas of a motor are home appliances, industrial automation, computers, aerospace, military, robotics, household products, etc. [1]. The electric motors are used in fans, vacuum cleaners, drill machines, hard disk drives, juicers, mobile phones, cars, aero planes, helicopters, clocks, fridges, hair dryers, water pumps, washing machines, DVD players, electric vehicles, industrial equipments, computers, toys, etc.

Energy crises in most of the parts of world have let the policy makers to rethink their policy for power consumption patterns. Most of the Asian countries have faced the high energy prices so they are focusing on using appliances which consume less power. Recently, Japan and some other Asian countries have implemented the variable speed Permanent Magnet (PM) motor drives in air conditioners and refrigerators to save energy [2]. The increase in energy prices has increased the demand of low power devices which can work on same performance but consume less energy. In this aspect the installation of variable speed PM motor drives is increased specially in automobile industry which has created a demand of Brushless DC (BLDC) motor [1] and it is the main reason of interest in BLDC motor.

Brushless DC (BLDC) motors completely eliminate the need of brushes hence increase the life and efficiency and decrease the maintenance cost. The demand of BLDC motor had been increased with a great pace in the late 19^{th} century and it is continuously increasing around the world up till now. The power consumption is the most critical issue nowadays and the low power consumption capability of BLDC motor has increased its demand a lot. Especially in Japan the energy crises had force them to use BLDC motor in newer appliances like refrigerators and air conditioners [2]. The rotor of BLDC motor is made up of permanent magnet and the stator is energized by determining the position of the rotor, so the need of brushes and commutator is eliminated in BLDC motors and has been replaced by intelligent electronic controller [3]. Hence the reliability and efficiency has been increased.

1.2 Description of a BLDC motor

The electrical motors which require an electrical connection between armature and rotor is generally treated as brushed motors or motors with brushes to pass electrical current while those electrical motors which do not require any such linkage is regarded as brushless motors or brushless permanent magnet (PM) motors [4].

BLDC motors are also known as Permanent Magnet DC Synchronous motors (PMSM) and these are best known for their characteristics and performance [1]. The demand of BLDC motor is increasing in all sectors in general and in industrial sector in particular for its best suitable conditions like low cost, small size, low power consumption and long operating life cycle.

BLDC motor works on electrical commutation rather than mechanical commutation as in brushed DC motors. Also, the permanent magnet (PM) works as a rotor and it rotates while the armature in BLDC motor remains static which leads to an issue of current transfer i.e. how to transfer current to the armature. In BLDC motor, an intelligent electronic controller is installed instead of brushed mechanism or commutator which helps in transferring current to the armature [1].

Furthermore, these motors are categorized by the shape of back-EMF and PMs mounting style which are shown in figure below:

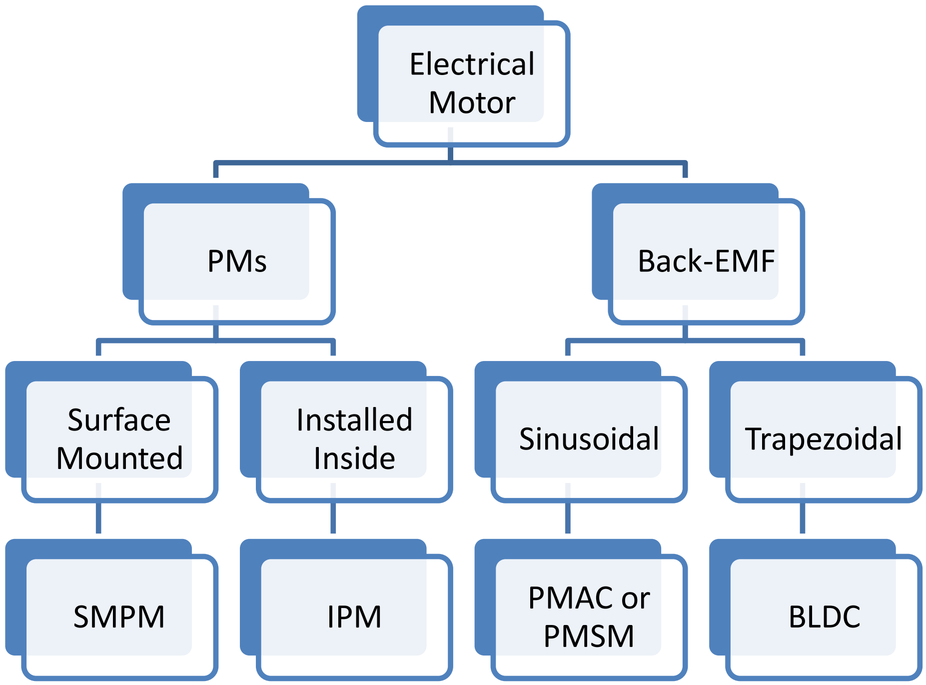

Fig. 1.1: Categorization of Electrical Motors on the basis of PMs and Back - EMF

The permanent magnet can be surface mounted on the rotor or installed inside of the rotor. The surface mounted configuration is considered as surface mounted permanent magnet (SMPM) while inside installation is treated as interior permanent magnet (IPM) [5]. Similarly, as indicated in figure 1.1 the back – EMF shape can be categorized as either sinusoidal or trapezoidal. The sinusoidal back – EMF shape determines the permanent magnet AC synchronous motor (PMAC or PMSM) and the trapezoidal back – EMF shows the Brushless DC motor (BLDC or BPM). One important thing to note is that the PMAC motor is excited by three – phase sinusoidal current and a BLDC motor is energized by a couple of currents with a quasi – square waveform [6, 7].

PM motors offer benefits like reliability, maintenance free nature, efficiency, high power density and noiseless operation, so these motors are widely used in several applications like aerospace, computers, industrial automation, military (combat vehicles) [3], automotive (hybrid vehicles) [8] and household products.

PM BLDC motors are electronically controlled hence it need the accurate information of rotor position to energize the stator windings. To determine the rotor position, position sensors may be used but it would damage the reliability factor and it is not feasible to use sensors in applications where reliability is more important. On one side position sensors have limitations and on other side powerful microprocessors are available, so it fastens the development of sensorless control techniques.

1.3 Advantages of Brushless DC motor over Brushed DC motor

The BLDC motor provides a lot many advantages over brushed DC motor [2]. The brushed DC motor needs maintenance due to the wear and tear of brushes and commutator, in BLDC motor the nature is maintenance free as it do not uses brushes and commutator so it has longer operating life. BLDC motor has better characteristics as well and the major benefits of BLDCM are high efficiency, better reliability, low power consumption, small size, low weight, longer operating life, high dynamic response, maintenance free nature, reduced Electromagnetic Interference and better speed versus torque characteristics [1]. BLDC motors offers following phenomenal advantages over brushed DC motors:

- Long operating life due to no brush erosion
- Smaller in size and cheaper
- Better speed versus torque characteristics
- Noiseless operation
- High efficiency and reliability
- Reduction of electromagnetic interference (EMI)
- Higher speed ranges
- Better dynamic response
- Better torque to size ratio

BLDCM has several advantages as listed above, but it has few limitations too. The rotor of BLDC is permanent magnet that is why the BLDC motor (BLDCM) is also known as Permanent magnet DC synchronous motors (PMDCM) [1]. It becomes difficult to pass current through the moving rotor so it becomes necessary to know the rotor position for which two methods are used i.e. with the help of sensors or by using sensorless techniques.

1.4 Controlling methods of BLDC motors

BLDC motor can be controlled by any of the following two methods:

1. Using sensors
2. Without using sensors i.e. Sensorless techniques

The sensors used in BLDC motor are Hall-effect sensors [1], Electromagnetic variable reluctance (VR) sensors [10] or Accelerometers [11] but it increases the cost and size due to the installation of the sensors in the BLDCM and the reliability also decreases as the sensors efficiency may damage with the passage of time. On the other hand the sensorless technique may eliminate the above drawbacks but the design becomes more complicated and the requirement of efficient control algorithm arises [3].

In general, the benefits of using BLDC motor are reduced in sensors based techniques as the additional electronic circuits and sensors has the same issue of wear and tear as which were present in brushed DC motor. So in sensor based methods the operating life and reliability is less as compared to sensorless techniques, however; the sensorless methods adds complexity to the control algorithms design. The main benefit of sensorless techniques is that the sensing circuit is removed hence the overall cost is reduced while the drawback of such techniques is that the requirements of control algorithm is increased and the complications of electronic circuits is also increased by manifold [3].

The sensorless techniques include Back EMF sensing methods and estimation methods as shown in figure below.

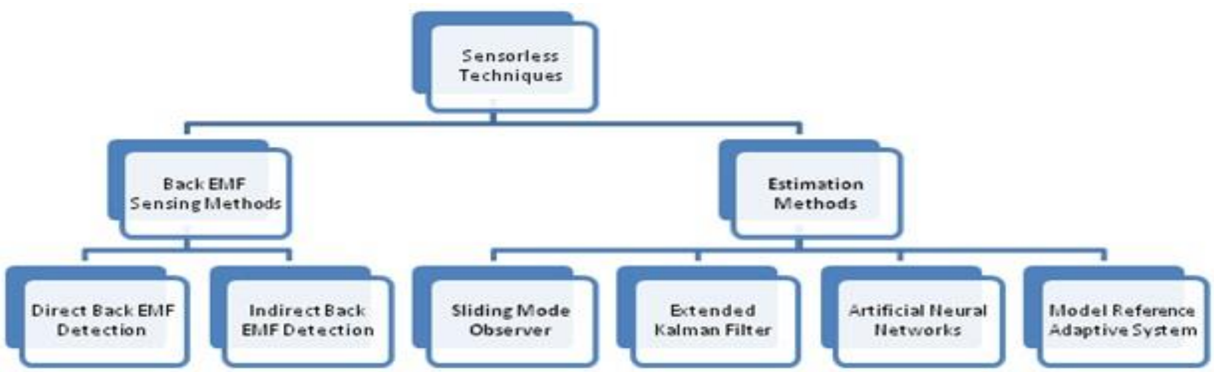

Fig. 1.2: Major sensorless techniques

Estimation algorithm can be used to calculate the speed of the motor and it can be applied to BLDC motor as well. It is better to assume initially the state vector of the system to be controlled as the measurement of the entire state vector usually is not possible especially in complex systems like BLDC motor. Once the state vector is available, the control law can be computed. So in case of control design problem, the method can be divided in to two phases. First is the computation of the control law by assuming that the state vector is available; second, is the design of a system that produces an approximation to the state vector which is known as the observer [1]. The following estimation or model based methods can be used: Sliding Mode Observer (SMO), Extended Kalman filter (EKF), Model Reference Adaptive system (MRAS), Artificial Neural Networks (ANN).

In this thesis, we will limit our discussion to Sliding Mode Observer. Sliding Mode Control is widely studied in the field of motion control and can be applied to control the speed of Brushless DC motors. Estimation algorithm based on SMO, can be used to calculate the speed and stator resistance independently [1]. This method faces few restrictions i.e. it requires high voltages from the power supply and intense load is bear by the static power converters. The prime advantage of SMO is its robustness.

In this work, the SMO estimates the phase to phase trapezoidal back-EMF in the un-driven coils by using the stator current and voltages which leads towards the measurement of six rotor positions of the BLDC motor via Zero crossing detectors (ZCD). The mathematical relation between rotor speed and back-EMF is also presented in this work to estimate the speed of the BLDC motor.

1.5 Thesis Organization

The thesis is divided in to following chapters:

Chapter 2 describes the literature review of the progress in the domain of sensorless techniques specially sliding mode observer for speed control of BLDCM.

Chapter 3 specifies the complete mathematical model of BLDC motor for speed controlling with specific focus on sliding mode control. It presents the zero crossing detection (ZCD) circuit which is used to estimate the six rotor positions of BLDCM and also elaborates the mathematical relationship between speed and Back-EMF.

Chapter 4 delineates the overall performance in detail by implementing the sliding mode observer on BLDC motor. The simulation results will be presented and discussed.

Chapter 5 finally concludes the thesis work by outlining the working of the proposed scheme, the novelty introduced in the basic idea, its benefits and the recommendations for future.

Chapter 2

2. Literature Review

2.1 Position and speed control of BLDCM using sensors

A position sensor is usually required to detect the exact position of rotor to perform the phase commutations in a PM motor drive. For PMAC motors, continuous position information is mandatory so a high resolution position sensor is used such as encoder. Whereas for BLDCM, only six phase commutation points per electrical cycle are required so low resolution sensors can be used as well to save the cost of sensing circuits like Hall-effect sensors, variable reluctance (VR) sensors and/or accelerometers.

2.1.1 Hall-effect sensors

These sensors work on the principle of Hall-effect theory which was discovered by Edwin Hall in 1879. In a BLDC motor the commutation is performed electronically hence it is required to energize the stator winding in a sequence. So, it is needed that the rotor position should be known so that proper sequence of energizing could be followed. In order to sense the rotor position, Hall-effect sensors may be installed in to the stator [12].

Mostly, three Hall-effect sensors are installed inside the stator at non-driving end of the BLDCM. Each sensor gives two readings of high and low when the magnetic poles (i.e. North or South Pole) of rotor pass near the sensor. The combination of three Hall-effect sensors helps to determine the sequence of six commutation points. Figure 2.1 shows the installation of Hall-effect sensors on stationary part of the BLDC motor and also the rotor with PM North and South Pole is shown.

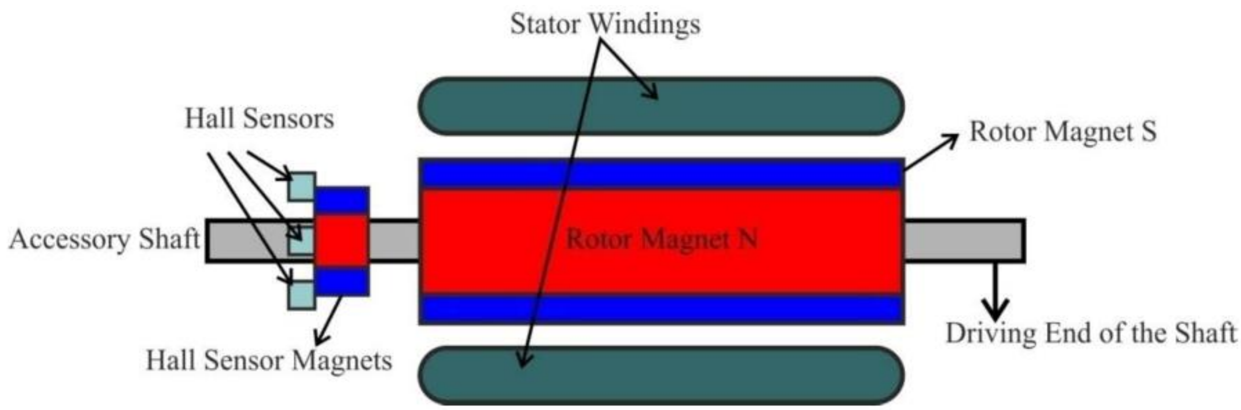

Fig. 2.1: BLDC motor transverse section showing Hall-effect sensors PM rotor [13]

Installation of Hall sensors in to the stator is a critical process and any sort of inaccuracy would result in wrong position of rotor i.e. error would be generated. Hall sensors should be exactly aligned with the rotor magnets for correct position information determination. Hall sensors are usually installed on printed circuit board (PCB) which is adjustable for calibration purposes with the rotor magnets for accurate results of position information [13].

2.1.2 Variable reluctance (VR) wheel speed sensors

VR sensor is a unique sensor in its kind and considered as a passive sensor as it do not require any power supply. It determines the position and speed of moving metal objects. The main components of VR sensor are listed below and also shown in figure 2.2

I. PM
II. Ferromagnetic pole piece
III. Rotating toothed wheel
IV. Pickup coil

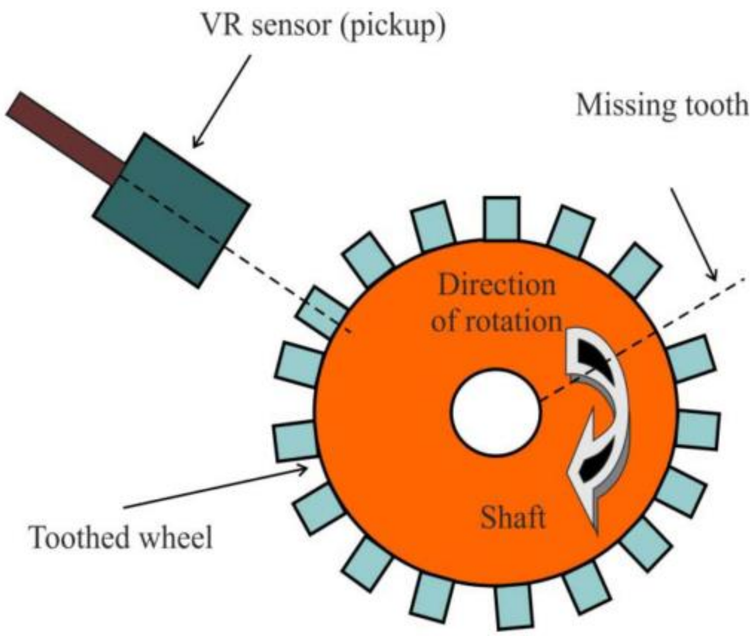

Fig. 2.2: VR sensor senses movement of toothed wheel [14]

This package is generally a PM with wire wrapped around it. In this type of sensor the polarity is not important and it works on the principle of magnetic induction [14]. The magnetic flux varies as the tooth passes through the magnetic field of VR sensor. The flux is maximum, when the tooth gear is near and it is minimum when the tooth gear is far away from the VR sensor. The moving wheel generates an analog wave and the frequency and voltage of this signal is proportional to the velocity of the rotating toothed wheel. Each teeth generates a pulse and the combination of pulses known as digital waveform can be further interpreted by the BLDCM controller.

Major advantages of this technique are listed below [14]:

- Cheap as compared to other methods like Hall-effect sensors
- Robust
- Can operate at more than 300 ^{0}C
- No power supply required
- Highly reliable as less wiring is required

VR sensors can be installed at small places due to its exceptionally small size and can be easily contained in protective cases to avoid risk of high temperature, high pressure and chemical attacks [15]. The wires of VR might be damaged inside the motor casing in harsh environment. In this aspect, the electromagnetic pulses from sensor should be transferred wirelessly to the motor controller and the package should be powerless as well so that the wires would be avoided [16].

2.1.3 Accelerometers

It's an electromechanical device which calculates the acceleration and it works on the principle of Hooke's law of spring motion and Newton's law of mass movement [15]. Diagrammatic representation of such system is shown in figure 2.3.

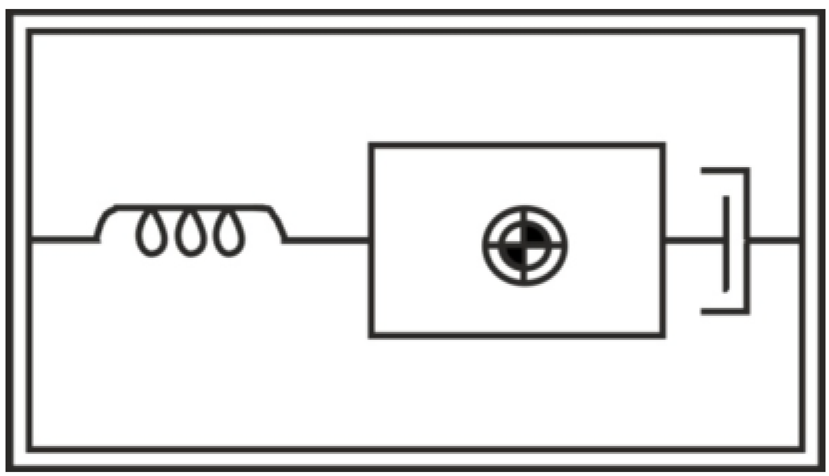

Fig. 2.3: Basic Spring Mass system Accelerometer [15]

Under acceleration the mass is displaced accordingly i.e. more acceleration means more displacement and vice versa. When mass is displaced, the displacement is calculated and using the equation 2.1 and 2.2 acceleration could be determined.

$$a = \frac{k}{m} \Delta x \tag{2.1}$$

Where, k is the spring constant, m is the mass and Δx is the displacement of spring. The force of displacement is given by the Hooke's law and Newton's law as:

$$F = k\,\Delta x \tag{2.2}$$

Many type of accelerometers are available, some of them are piezoresistive, linear variable differential transformers (LVDT), piezoelectric, potentiometric, etc. [15]. Latest accelerometers are based on micro electromechanical systems (MEMS) and can be easily integrated with signal processors [16].

2.1.4 Conventional control method using sensors

BLDC motor is operated by voltage pulses which energizes the active phases of the three phase winding system. The voltage pulses should be accurately applied so that the angle between stator and rotor flux is near to 90^0 so that maximum torque would be generated. Therefore, rotor position with respect to stator coil is required by the controller that may be achieved by Hall-effect sensors which can detect magnetic field of passing rotor magnets. Each sensor provide high and low pulses after every 180^0 hence three sensors are separated by 60^0 from each other and this sequence divides the rotation in to six phases constituting a 3 bit code [12].

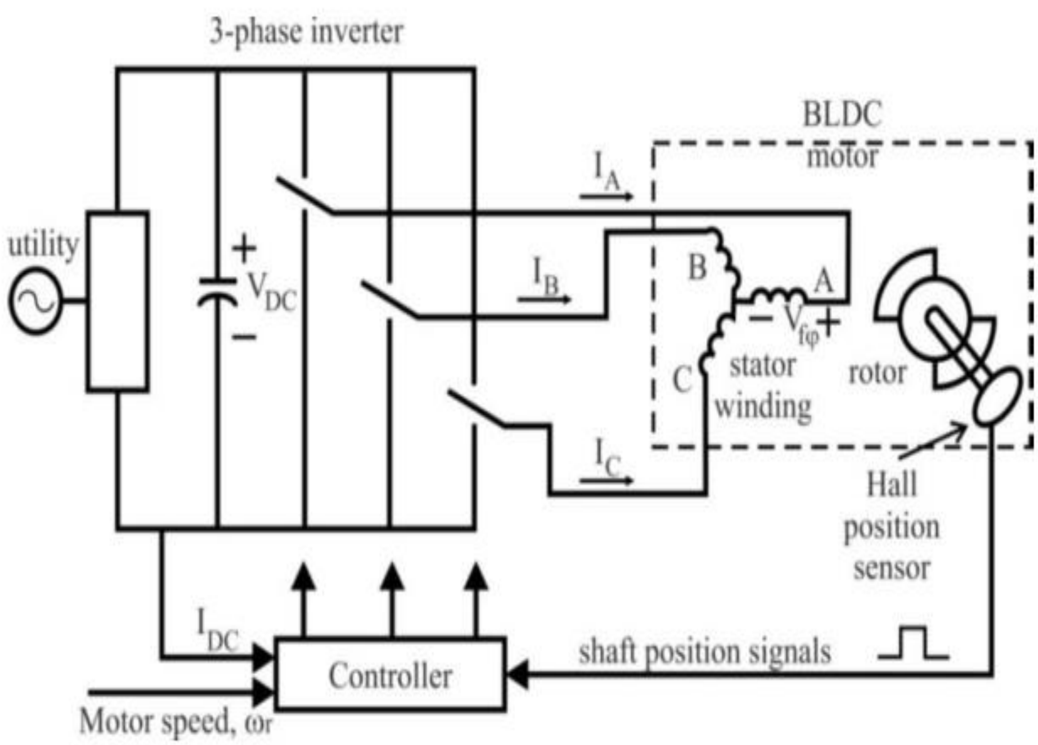

Fig. 2.4: Electronically commutated BLDC motor drive [18]

Switching the current in a way that only two phases conducts at a time for every 60^0 rotation of rotor is known as electronic commutation. The Hall-effect sensors generate digital pulses which are used to determine the three phase switching sequence [17]. BLDC motor drive with six step inverter and Hall-effect sensors is shown in figure 2.4. This drive has an internal current loop for stator current and outer speed loop for speed control [18]. PWM is used to control the six switches of the three phase bridge by varying the duty cycle, hence controlling the speed of the motor.

In the inverter section, only two switches conduct at a time each from upper and lower section which ensures that the sequence of conducting pairs of stator terminals is maintained [18]. Figure 6 shows three Hall-effect sensors producing six back-EMFs which in turn generating three phase currents.

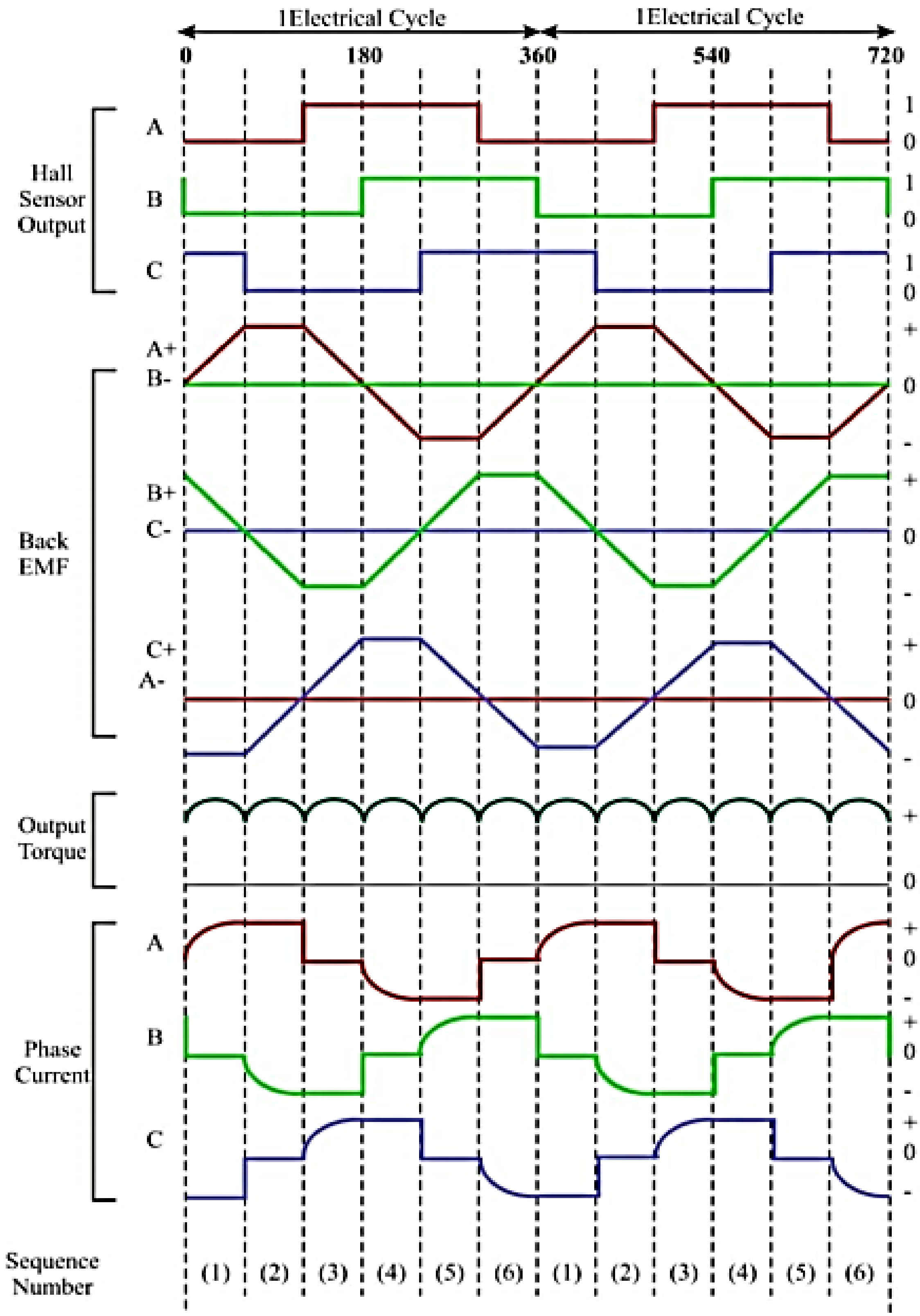

Fig. 2.5: Hall sensor signal, Back-EMF, output torque and phase current [13]

PM motor drives need rotor position sensor for phase commutation but the sensor introduces several drawbacks like [7]:

- Cost and size of the motor is increased
- complexity in installing sensors
- Hall sensors are sensitive to temperature, so it limits the range of operation
- Reduced reliability due to additional components and wiring

To increase the reliability and decrease the additional cost incurred in the installation of sensors, sensorless techniques may be used instead of position sensors. So far many sensorless techniques are carried out for speed and position control of BLDC motors as discussed in [6]. In the next section we will discuss few methods of sensorless techniques for position and speed control.

2.2 Position and speed control using sensorless techniques

Fringe benefits of cost and size reduction can be obtained by removing the position sensor(s) and it helps in applications where only variable speed is required i.e. position is not of prime importance. In general, some control techniques like back EMF sensing method and current sensing method provide some information of position from which somehow accurate information of rotor position can be extracted. Hence this information may help in operating the motor with synchronous phase currents. A permanent magnet brushless drive which works on electrical measurements instead of position sensors is known as sensorless drive [4].

A unique feature of three phase BLDC motor is that during excitation its two out of three phase windings are conducting at a time while the idle (third) phase caries the back electromotive forces (back - EMFs). This back-EMF estimates the position of rotor which is a cheap method to estimate the rotor position information. Although many sensorless control techniques are discussed in [6], most popular method is back – EMF sensing system [19]. Obtaining the commutation sequence by observing the back-EMF on unused phase is most cost effective method especially in star wound motors; however, this method is not desirable at low speed as it did not detect zero crossing at low speed due to large signal to noise ratio. At standstill, back-

EMF is zero and proportional to speed so in back-EMF based sensing techniques, low speed performance is limited and an open loop starting strategy is required [20].

In general, BLDC motor consists of three parts as mentioned below according to [21] which are also shown in figure 2.6:

1. PMSM (electrical to mechanical energy converter)
2. Inverter (equivalent to brushes and commutators)
3. Shaft position sensor

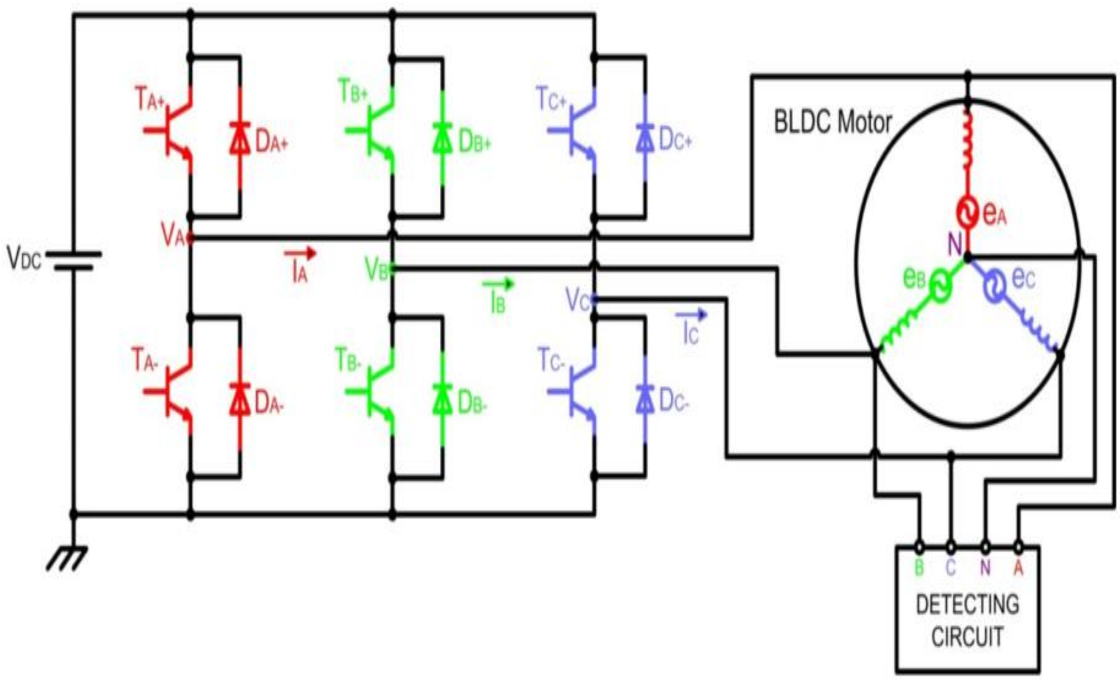

Fig. 2.6: Typical sensorless BLDC motor drive [21]

The initial position of rotor is determined by the stator iron of the BLDC motor which has a non-linear magnetic saturation characteristic. Energizing the stator winding results in a magnetic field in particular direction and simultaneously different current responses are generated due to the difference in inductance and this variation in current results in estimation of rotor position [22]. Hence, inductance of stator winding is a function of the rotor position.

Back-EMF sensing techniques are divided in two main areas as mentioned below:

2.2.1 Direct back-EMF detection methods

In direct back-EMF detection, the floating phase is checked and the zero crossing detection (ZCD) circuit identifies the zero crossing by matching it against neutral point voltage. The main issues with this method are its high common mode voltage and high frequency noise due to the pulse width modulation (PWM) drive. To deal with above two issues, this method needs low pass filters and voltage dividers. Direct back-EMF detection methods are further categorized as:

- Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing.
- PWM strategies.

2.2.2 Indirect back-EMF detection methods

The filters used in direct back-EMF detection method causes commutation delay at high speeds and the voltage dividers causes attenuation which results in reduction in signal sensitivity at low speeds. So, direct back-EMF faces problem at both high and low speeds hence the resultant speed range is narrowed. Following indirect back-EMF detection methods are used to reduce the switching noise.

- Back-EMF Integration.
- Third Harmonic Voltage Integration.
- Free-wheeling Diode Conduction or Terminal Current Sensing.

All above methods are out of the scope of this work, so they are not discussed in detail in this thesis. Only first method i.e. back-EMF ZCD method is discussed below to show the idea for working of back-EMF techniques.

2.2.1.1 <u>Back EMF Zero Crossing Detection method (Terminal Voltage Sensing):</u>

It is the basic approach of back-EMF sensing method in which the back-EMF is detected from unexcited phase when it crosses zero.

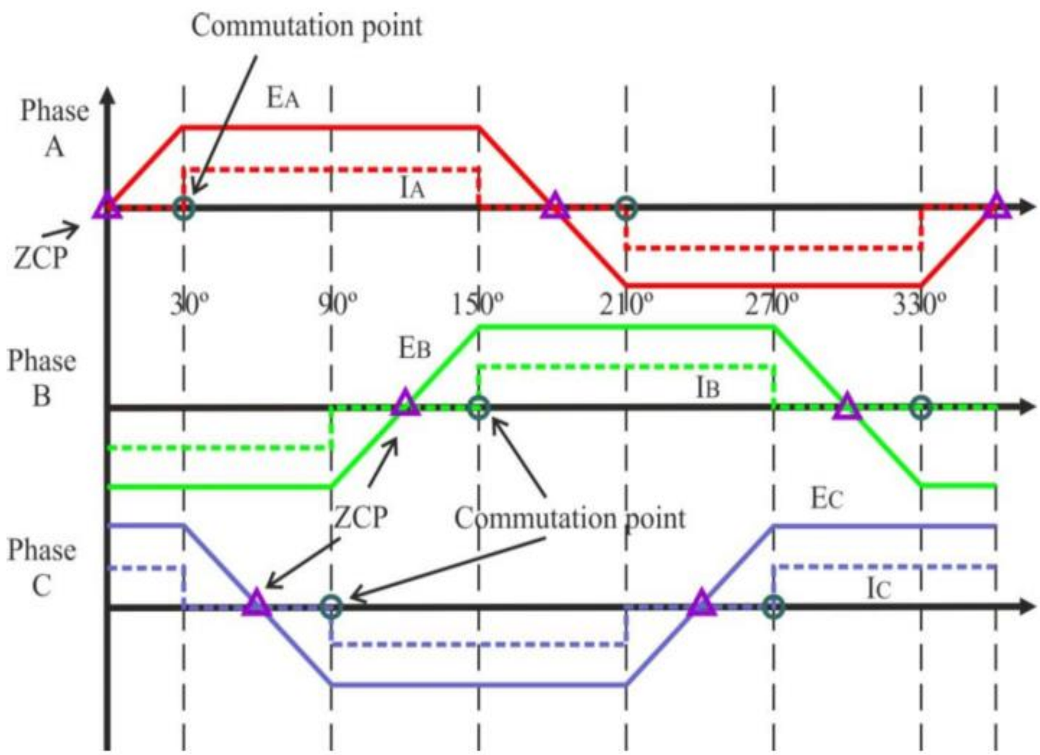

Fig. 2.7: Zero crossing points of the back-EMF and the phase commutation points [25]

In three-phase BLDC motor the back-EMF can be detected indirectly from one of the three phase windings which helps in extracting the rotor position information and it is also known that from each terminal voltage two commutation points are extracted. As indicated in figure 2.6 that total six commutation points are required and by calculating the time interval between two commutation points at terminal voltage, four other commutation points can be interpolated while considering that the speed of motor is constant over consecutive electrical cycles. A low pass filter or band pass filter is used depending on the terminal voltage sensing locations for position information retrieval hence resulting in elimination of remaining two terminal voltages so that the overall cost and complexity of sensing circuits is reduced. Also, the digital filtering method checks out the true and false zero crossing points (ZCPs) of phase back-EMF, which are generated by terminal voltage spikes due to phase commutations hence improving the ZCD method [23].

ZCP of back-EMF can also be determined without using the neutral potential by measuring the voltage difference between two line voltages as shown in [24]. Another method of phase locked loop (PLL) can be used as sensorless commutation by sensing the phase winding back-EMF voltages as worked out in [25]. However, the PLL method uses phase detector which has a limitation of narrow speed range and also the PLL is sensitive to switching noise. For simplification, a sensorless controller chip ML4425 from Fairchild semiconductor can be used to build the driver design [26, 27].

Instead of back-EMF ZCD technique a more effective method of torque generation can be used which is currently in development stages and it can be applied to automotive applications like design of motor pump units [4]. The method is known as sensorless Field Oriented Control (FOC) of BLDCM [28].

The back-EMF detection method is not best suitable at low speed operations and at standstill as it is proportional to the speed of motor. To cater this issue, an initial procedure can be adopted which would start the motor from standstill [22]. Some applications like actuators of aviation system need precise and accurate start-up of DC motor. In open loop control, PWM signal starts the electrical commutation which drives the transistor power stage without any position feedback as shown in figure 2.6 [3].

Long settling time of power devices can cause false ZCD of back-EMF at high speeds. To cater this issue, back-EMF is sensed during on time at high duty cycle as in [29], so that the transient is settled down. Hence, at motor start-up and at low speed, original method is used as there is no signal attenuation whereas at high speed, the system may be shifted to improved back-EMF sensing method. By joining both detection methods, a new system is generated which runs excellently over a wide speed range [30, 31].

As the basic method of back-EMF sensing techniques is discussed, now further methods with the relevant study would be only mentioned and can be studied in detail from the indicated sources.

- Third Harmonic Voltage Integration method can be viewed in detail from [34, 35]
- Free-wheeling Diodes Conduction Detection method (Terminal Current Sensing) can be studied from [21]
- Back-EMF Integration Method is defined in detail at [32]

- Methods based on PWM strategies:
  - Conventional 120° PWM technique is elaborated in [36]
  - Technique of virtual neutral point elimination is explained at [30]
  - Technique for low speed or low voltage applications is discussed in [31, 33, 37]
  - Technique for high speed or high voltage applications is described at [37, 38]
  - Technique for small power applications is defined in [33, 36, 39]
  - Direct current controlled PWM technique (hysteresis current control) is discussed in [21]

2.3 Other Sensorless Techniques:

It is better to assume that the state vector of the entire system is available through measurements otherwise it would be difficult to device the control law for the system. If the entire state vector cannot be determined by measurement which is mostly the case especially in complex systems, then the determined control law cannot be used or it would not perform appropriately. Hence, a methodology to calculate the entire state vector needs to be determined or an appropriate approximation for the state vector which is suitable for the control law should be defined [56]. In general, it is always more convenient and feasible to approximate the state vector rather than determining the actual design of the system.

In this scenario, control design problem is a two-step procedure. First step is to devise the control law by assuming that the state vector is known. The second step is the designing of a system which estimates the state vector. This system is known as observer, which has all the inputs and available outputs of the system whose state is to be approximated and it has the state vector that is linearly related to the desired approximation [40]. Apart from the simplicity of the method, the best use of observer is that the states which are hard to determine from measurement can also be obtained [32]. Observers offer practical utility plus it also provide an associated theory on fundamental linear system concepts like controllability, dynamic response, Observability and stability [1].

An observer provides a mathematical model of BLDC motor which would compare the response (i.e. output) of actual system with the estimated output and the error between both outputs would fed in to the system which would correct the estimated model or estimated values i.e. rotor position and speed so that the difference between both models approaches zero [35]. The design of observer vary from type of motor model used like for PMAC motor the back-EMF is sinusoidal and it require continuous feedback while for BLDC motor, the back-EMF is trapezoidal and it require only six commutation points for one electrical cycle and continuous position information is not necessary [32].

Many observer based models are under development phase as mentioned below, but we would put our major focus on Sliding Mode Observer.

- Sliding Mode Observer (SMO)
- Extended Kalman Filter (EKF)
- Model Reference Adaptive System (MRAS)
- Adaptive Observers
- Artificial Neural Networks (ANN)

2.3.1 Sliding Mode Observer:

BLDC motor is controlled on the basis of its rotor position information, for which encoder or resolver is used to sense the rotor position. But, the position sensors are expensive and they also reduce the reliability and special arrangement needs to be done for mounting the sensors so in most applications the position sensors are not desirable. As the state equations of BLDC motor is non-linear, so linear theory cannot be easily applied. So, to improve the robustness and reliability and to reduce the cost of overall system, many estimation techniques are developed so far [41]. Some methods on Sliding Mode Observer are also developed which will be discussed here.

Speed and stator resistance are calculated by Zaky using SMO with popov's hyper-stability theory [42]. The system of BLDCM is non-linear and its control can be designed using SMO [43]. The issue this technique faces is the requirement of high voltages, while it offers benefits of robustness. Sliding mode observer provides better conditions for convergence and does not indulge the system in to undesirable chattering [41].

Chapter 3

3 Mathematical Modeling

3.1 Design of BLDC Motor:

The neutral point of BLDC motor is generally not accessible so it is not possible to measure the phase voltages directly. On the other hand two out of three phases conducts at a time so the BLDC motor is modeled in the abc framework as follows by considering the following relations:

$$\begin{aligned}
\frac{d}{dt}(I_a - I_b) &= -\frac{R}{L}(I_a - I_b) - \frac{1}{L}E_{ab} + \frac{1}{L}U_{ab} \\
\frac{d}{dt}(I_b - I_c) &= -\frac{R}{L}(I_b - I_c) - \frac{1}{L}E_{bc} + \frac{1}{L}U_{bc} \\
\frac{d}{dt}(I_c - I_a) &= -\frac{R}{L}(I_c - I_a) - \frac{1}{L}E_{ca} + \frac{1}{L}U_{ca}
\end{aligned} \tag{3.1}$$

Where, the currents (Ia − Ib),(Ib − Ic) or (Ic − Ia) are measured between two phases, E_{ab} , E_{bc} and E_{ca} are phase to phase back-EMF and U_{ab}, U_{bc} and U_{ca} are phase to phase voltages. To reduce the order of the BLDC motor in equation 3.1, consider two phases only i.e. (a − b) and (b − c) by assuming the following conditions: [8]

- The phase to phase back-EMF is trapezoidal, and its variation is very slow.
- The motor is unsaturated
- The armature reaction is negligible
- The phases are balanced

By considering two phases and above assumptions, model is shaped as follows:

$$\begin{aligned}
\frac{d}{dt}(I_a - I_b) &= -\frac{R}{L}(I_a - I_b) - \frac{1}{L}E_{ab} + \frac{1}{L}U_{ab} \\
\frac{d}{dt}(I_b - I_c) &= -\frac{R}{L}(I_b - I_c) - \frac{1}{L}E_{bc} + \frac{1}{L}U_{bc} \\
\frac{d}{dt}E_{ab} &= 0 \\
\frac{d}{dt}E_{bc} &= 0
\end{aligned} \tag{3.2}$$

The system is equation 3.2 can be expressed in state space form as:

$$\begin{aligned}
\dot{X}_1 &= -\alpha_1 X_1 - \alpha_2 X_3 + \alpha_2 V_1 \\
\dot{X}_2 &= -\alpha_1 X_2 - \alpha_2 X_4 + \alpha_2 V_2 \\
\dot{X}_3 &= 0 \\
\dot{X}_4 &= 0 \\
y_1 &= X_1 \\
y_2 &= X_2
\end{aligned} \tag{3.3}$$

Where, $X_1 = I_a - I_b$, $X_2 = I_b - I_c$, $X_3 = E_{ab}$ and $X_4 = E_{bc}$ are the state variables, $V_1 = U_{ab}$ and $V_2 = U_{bc}$ are the input variables, y_1 and y_2 represent the output variables and $\alpha_1 = \frac{R}{L}$ and $\alpha_2 = \frac{1}{L}$ are the systems parameters. Third back-EMF E_{ca} between two phases (c − a) can be calculated by the following equation by assuming that the system is balanced.

$$E_{ab} + E_{bc} + E_{ca} = 0 \tag{3.4}$$

3.2 Sliding Mode Observer Design

The system shown in equation 3 is a linear system with parametric uncertainty. The observer for the system can be designed as follows:

$$\begin{aligned}
\dot{\hat{X}}_1 &= -\alpha_1 X_1 - \alpha_2 \hat{X}_3 + \alpha_2 V_1 + K_1 I_s \\
\dot{\hat{X}}_2 &= -\alpha_1 X_2 - \alpha_2 \hat{X}_4 + \alpha_2 V_2 + K_2 I_s \\
\dot{\hat{X}}_3 &= K_3 I_s \\
\dot{\hat{X}}_4 &= K_4 I_s
\end{aligned} \tag{3.5}$$

Where, $K_1, K_2, K_3\ and\ K_4$ are the gains of the observer and can be defined as, $K_1 = (k_{11}, k_{12})$, $K_2 = (k_{21}, k_{22})$, $K_3 = (k_{31}, k_{32})$ and $K_4 = (k_{41}, k_{42})$. Similarly, the sliding surface $s = [S_1 \quad S_2]^T$ is represented as follows:

$$
\begin{gathered}
S = [s_1 \quad s_2]^T = \left[X_1 - \hat{X}_1 \quad X_2 - \hat{X}_2\right]^T = [0 \quad 0]^T \\
I_s = [sign\,(s_1) \quad sign\,(s_2)]^T
\end{gathered}
\tag{3.6}
$$

By using the observer gains and equation 6, the observer would take the form

$$
\begin{aligned}
\dot{\hat{X}}_1 &= -\alpha_1 X_1 - \alpha_2 \hat{X}_3 + \alpha_2 V_1 + k_{11} sign\left(X_1 - \hat{X}_1\right) + k_{12} sign\left(X_2 - \hat{X}_2\right) \\
\dot{\hat{X}}_2 &= -\alpha_1 X_2 - \alpha_2 \hat{X}_4 + \alpha_2 V_2 + k_{21} sign\left(X_1 - \hat{X}_1\right) + k_{22} sign\left(X_2 - \hat{X}_2\right) \\
\dot{\hat{X}}_3 &= k_{31} sign\left(X_1 - \hat{X}_1\right) + k_{32} sign\left(X_2 - \hat{X}_2\right) \\
\dot{\hat{X}}_4 &= k_{41} sign\left(X_1 - \hat{X}_1\right) + k_{42} sign\left(X_2 - \hat{X}_2\right)
\end{aligned}
\tag{3.7}
$$

The observer shown above, need the tuning of eight gains in such manner that the estimated state converge to the real state. As the task would be cumbersome so the above observer can be relaxed by reducing number of gains. To reduce the gains we set $k_{12} = k_{21} = k_{32} = k_{41} = 0$. Hence the observer in equation 7 would take the form:

$$
\begin{aligned}
\dot{\hat{X}}_1 &= -\alpha_1 X_1 - \alpha_2 \hat{X}_3 + \alpha_2 V_1 + k_{11} sign\left(X_1 - \hat{X}_1\right) \\
\dot{\hat{X}}_2 &= -\alpha_1 X_2 - \alpha_2 \hat{X}_4 + \alpha_2 V_2 + k_{22} sign\left(X_2 - \hat{X}_2\right) \\
\dot{\hat{X}}_3 &= k_{31} sign\left(X_1 - \hat{X}_1\right) \\
\dot{\hat{X}}_4 &= k_{42} sign\left(X_2 - \hat{X}_2\right)
\end{aligned}
\tag{3.8}
$$

The above observer indicated in eq. 3.8 would be used in the rest of the thesis. The working of the system is explained below.

3.3 System Explanation

The overall system is based on two loops i.e. inner loop which is the current loop and the outer loop which is the speed loop. In the inner loop, the Sliding Mode Observer determines the estimated phase to phase back EMFs i.e. $\hat{E}_{ab}, \hat{E}_{bc}$ and $\hat{E}_{ca}$ which in turn computes the six rotor positions using Zero Crossing Detector (ZCD) as shown in figure 3.1.

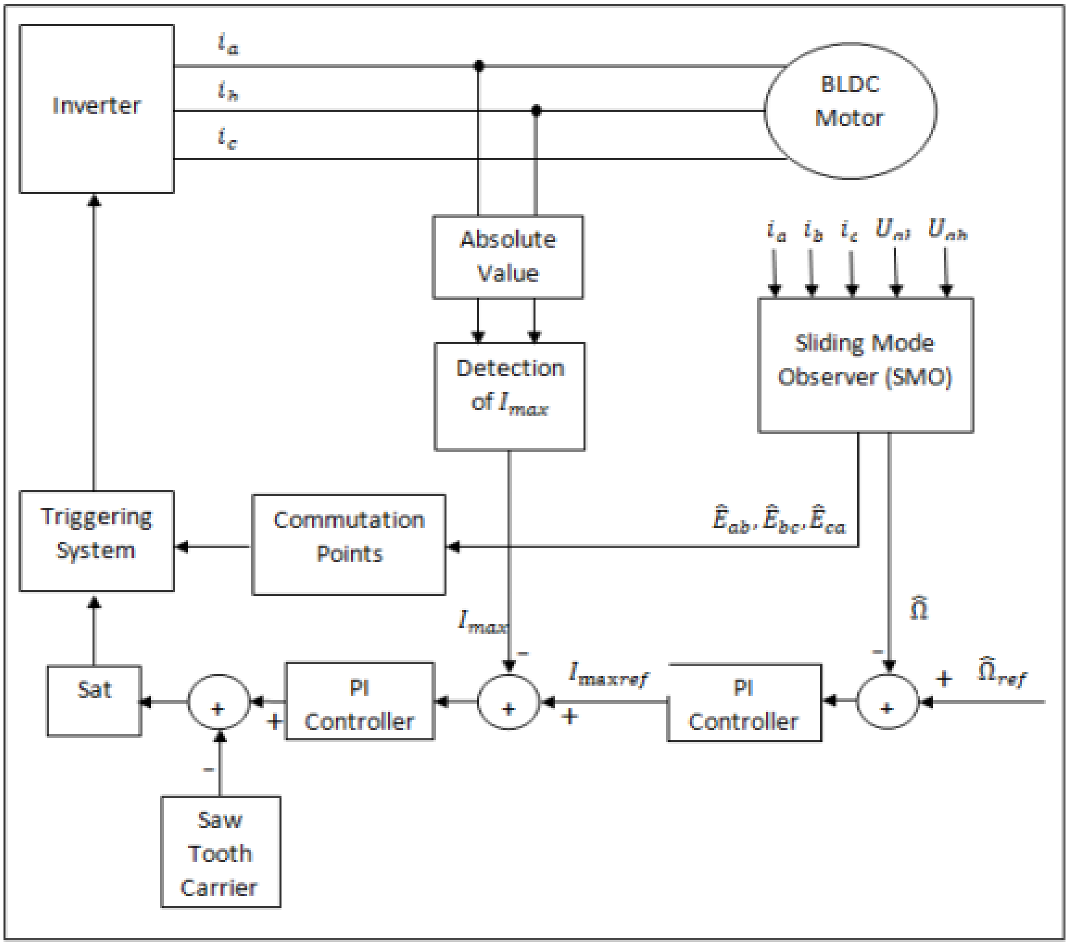

Fig. 3.1: Overall system representation of the proposed system

The commutation point block using ZCD is shown in figure 3.2. The Triggering block allow the commutation points to switch on and off the specified transistors in the inverter block which would operate the BLDC motor at the desired speed. The inverter block supplies a rectangular current waveform whose magnitude I_{max} varies according to the machine shaft torque. The DC current I_{max} is generated by sensing two armature currents and passing it through the absolute block.

The outer speed loop calculates the difference between the estimated speed by SMO and the reference speed which is tuned by the first PI Controller which is used as a speed regulator. The second PI Controller further tunes the difference of I_{max} and I_{ref} and its output is compared with the saw-tooth carrier to generate the Pulse Width Modulation (PWM). This PWM is used to activate a couple of six power transistors in the inverter circuit. The output of the commutation point block is used to decide which set of power transistors would be on and the output of Saturation function enable or disable the triggering circuit to allow or disallow the actions of commutation points on power transistors.

The circuit of Zero Crossing Detector is shown in figure 3.2. The ZCD circuit provides the six commutation points a, −a, b, −b, c and − c for the six power transistors by using the estimated phase to phase back EMFs i.e. $\hat{E}_{ab}, \hat{E}_{bc}$ and $\hat{E}_{ca}$.

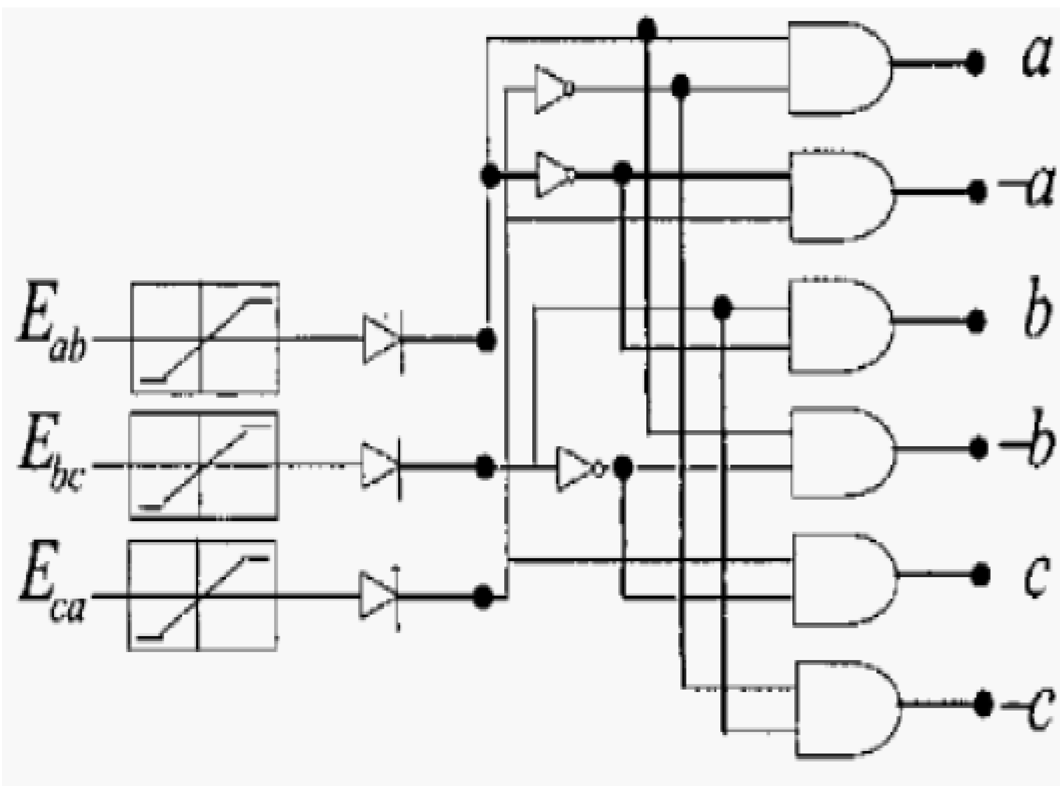

Fig. 3.2: Zero crossing detector circuit [44]

The commutation points are shown in figure 3.3 and figure 3.4.

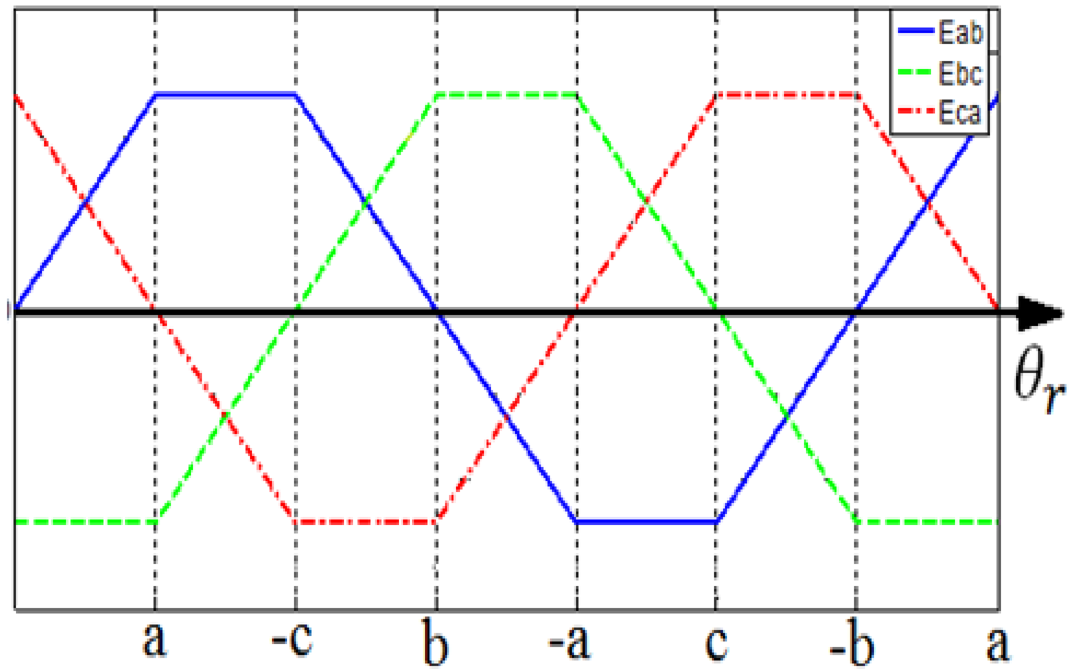

Fig. 3.3: Commutation points and phase to phase Back-EMFs

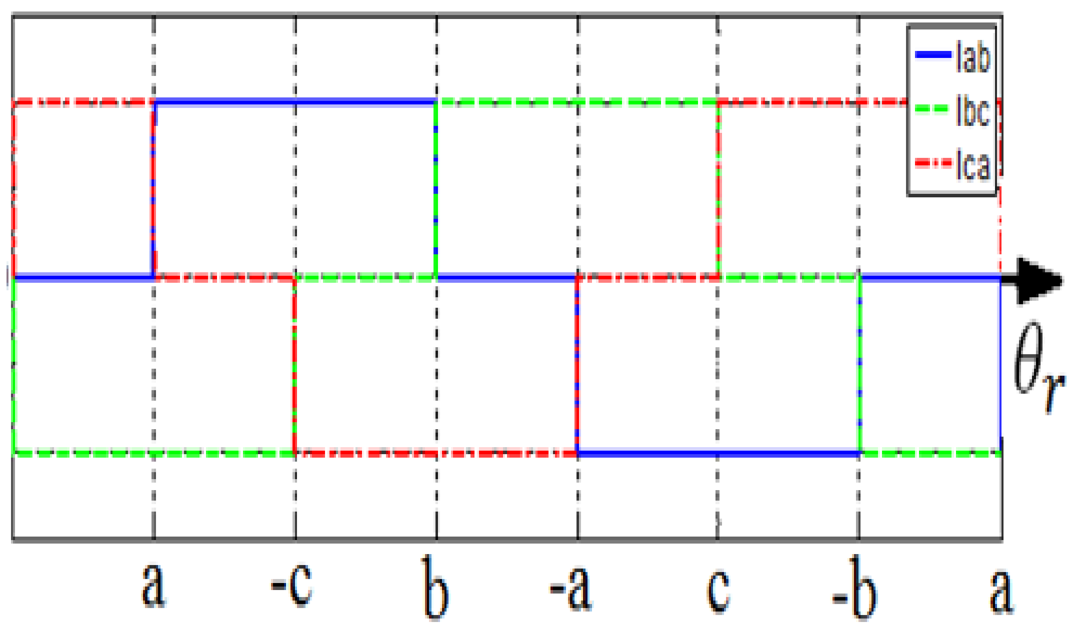

Fig. 3.4: Commutation points and phase currents

3.3.1 Rotor Speed Estimation:

The rotor speed can be calculated by using the phase to phase E_{max} as follows:

$$\omega_r = \frac{E_{\max\,(phase-to-phase)}}{2\,k_{emf}} \tag{3.9}$$

With,

$$E_{\max\,(phase-to-neutral)} = K_{EMF}\,\omega_r \tag{3.10}$$

And,

$$E_{\max\,(phase-to-neutral)} = \frac{E_{\max\,(phase-to-phase)}}{2} \tag{3.11}$$

Where, K_{EMF} is the constant of the back-EMF. The magnitude of $E_{\max\,(phase-to-phase)}$ can be determined by using the estimated phase to phase back EMF and six commutation points. Estimated phase to phase back EMF would be calculated by SMO block and the six commutation points would be determined by the Zero Crossing Detector (ZCD) block.

Chapter 4

4. Simulation Results:

To observe the performance of proposed SMO on Brushless DC Motor, following system is implemented on MATLAB/Simulink. The parameters used for the implementation of the model are:

- Stator Resistance: $R_s = 0.966\ \Omega$
- Inductance: $L_{cs} = 11.592\ mH$
- Poles: $\rho = 2$
- $K_e = 0.665\ V/rad/s$

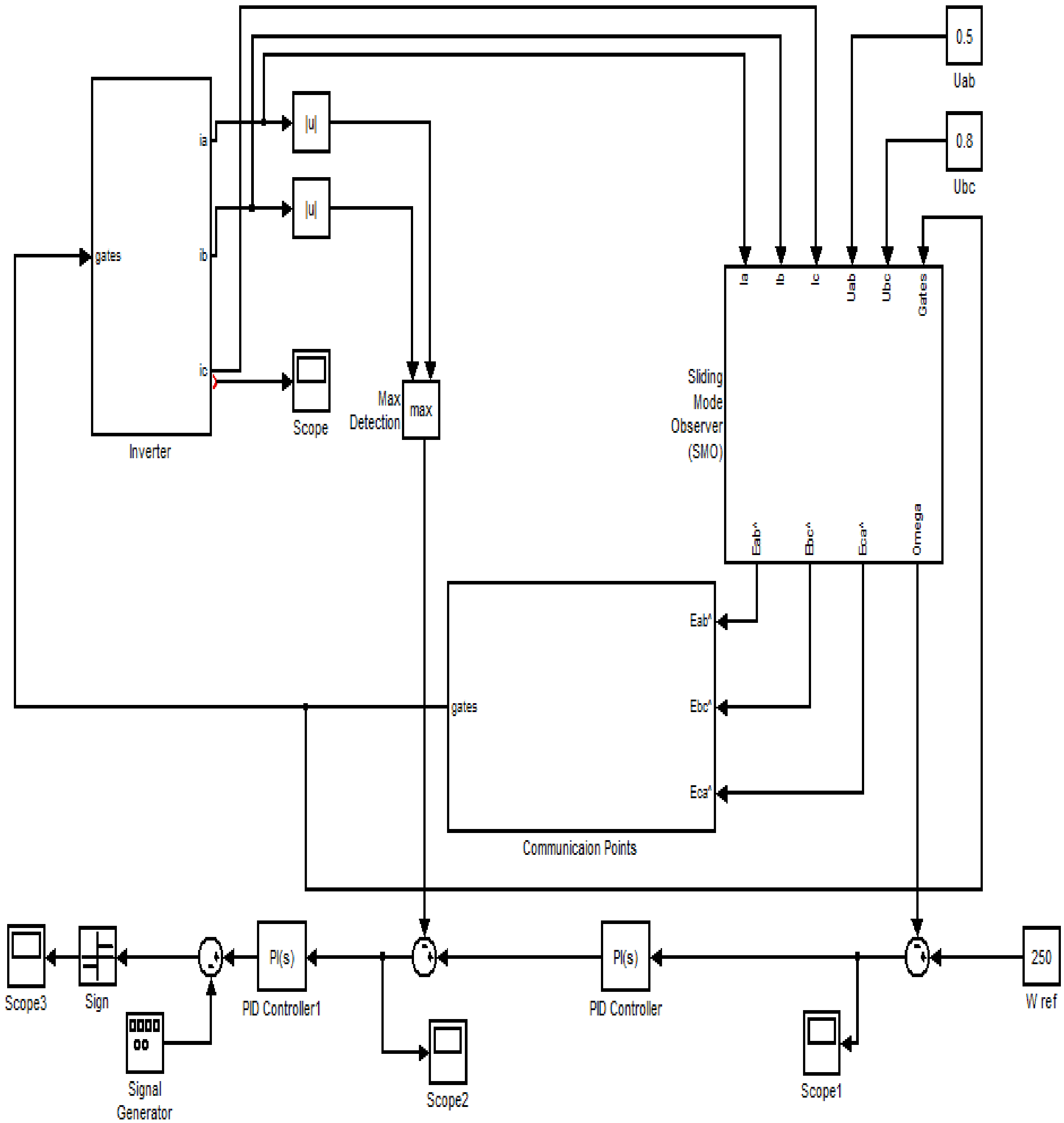

Fig. 4.1: Implementation of overall system model on Simulink

The design of the BLDC motor and sliding mode observer as indicated in eq. 3.3 and eq. 3.8 respectively along with certain assumptions is implemented on Simulink which is shown below in fig. 4.2. This block with the title of Sliding Mode Observer (SMO) as indicated in fig. 4.1 receives six inputs in all including currents $(i_a, i_b\ and\ i_c)$ of the BLDC motor, voltages $(U_{ab}\ and\ U_{bc})$ of BLDCM and gates for triggering the E_{max}. This block of SMO estimates phase to phase back-EMFs $(E_{ab}, E_{bc}\ and\ E_{ca})$ and generates the speed of the motor. The speed of the motor is then compared with the reference speed of 250 rpm. The error between the speeds is then fed in to the PI controller for gain settings. The output of first PI controller is compared with the maximum phase currents of the motor which in turn generates the difference of reference and actual current. Now, second PI controller again changes the gains to reduce the error and then sign function determines which gate to trigger. The triggering circuit then repeats the cycle and the error between reference speed and actual speed is gradually reduced to zero. The performance of the system is tested on several speeds, and the results shows that the sliding mode observer caters the reference speed in milliseconds time. The result on MATLAB would further clarify the response of the system.

The design of the observer on the basis of its mathematical modeling, which is shown in eq. 3.8, is implemented on MATLAB/SIMULINK. The observers for state X_1 and X_2 are shown in fig. 4.3 and fig. 4.4 respectively.

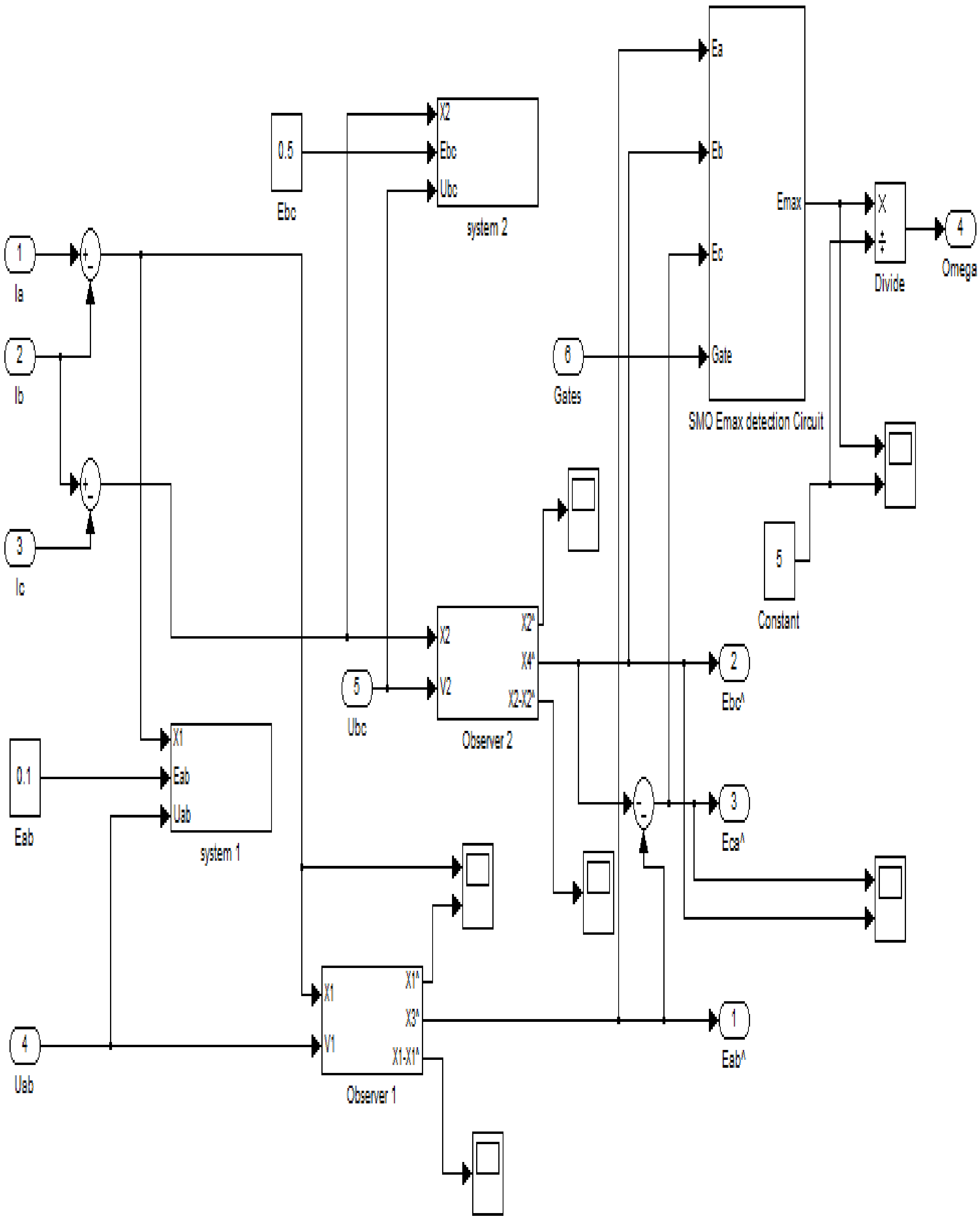

Fig. 4.2: BLDC motor and Sliding Mode Observer

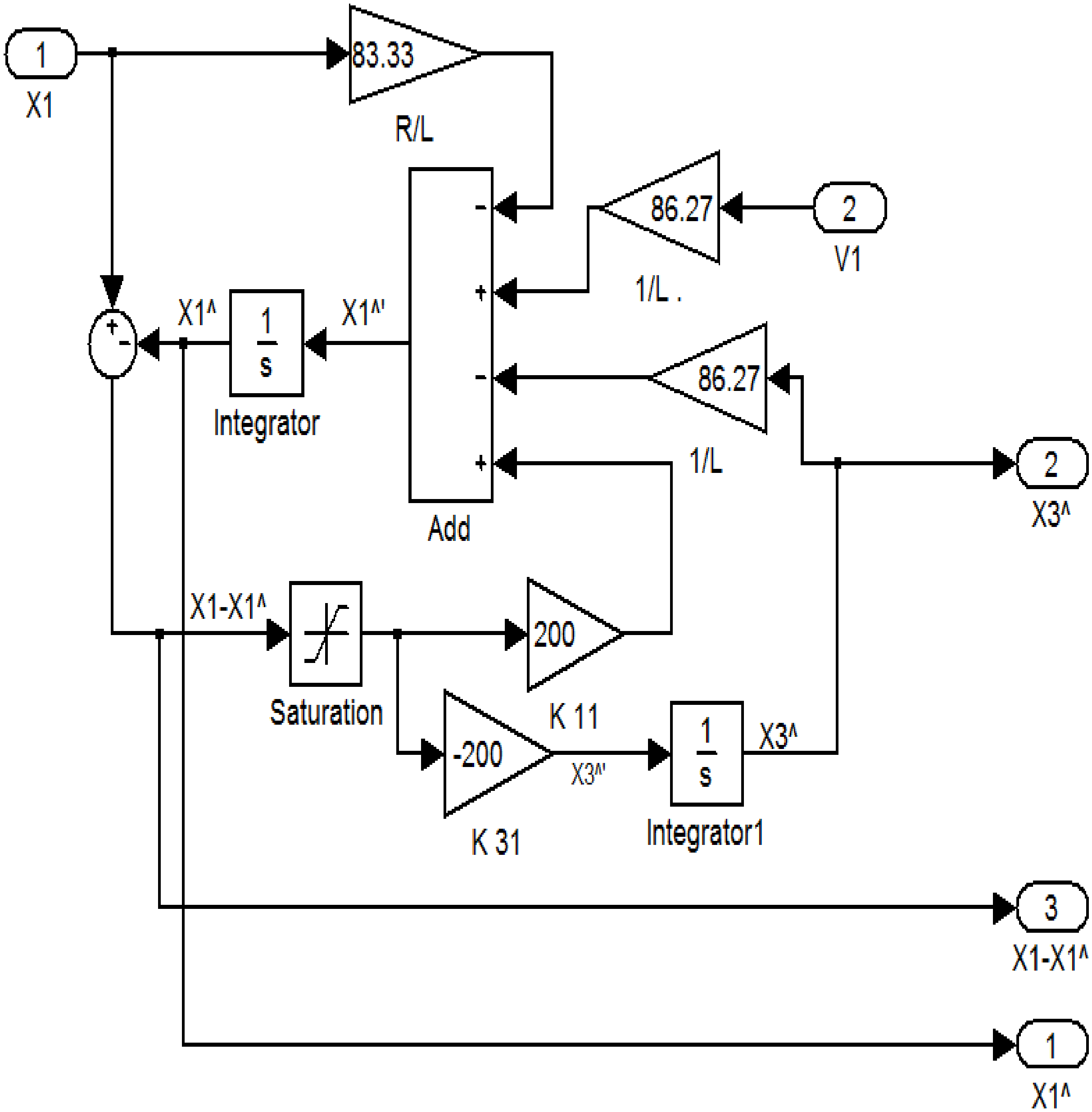

Fig. 4.3: Sliding Mode Observer for X_1

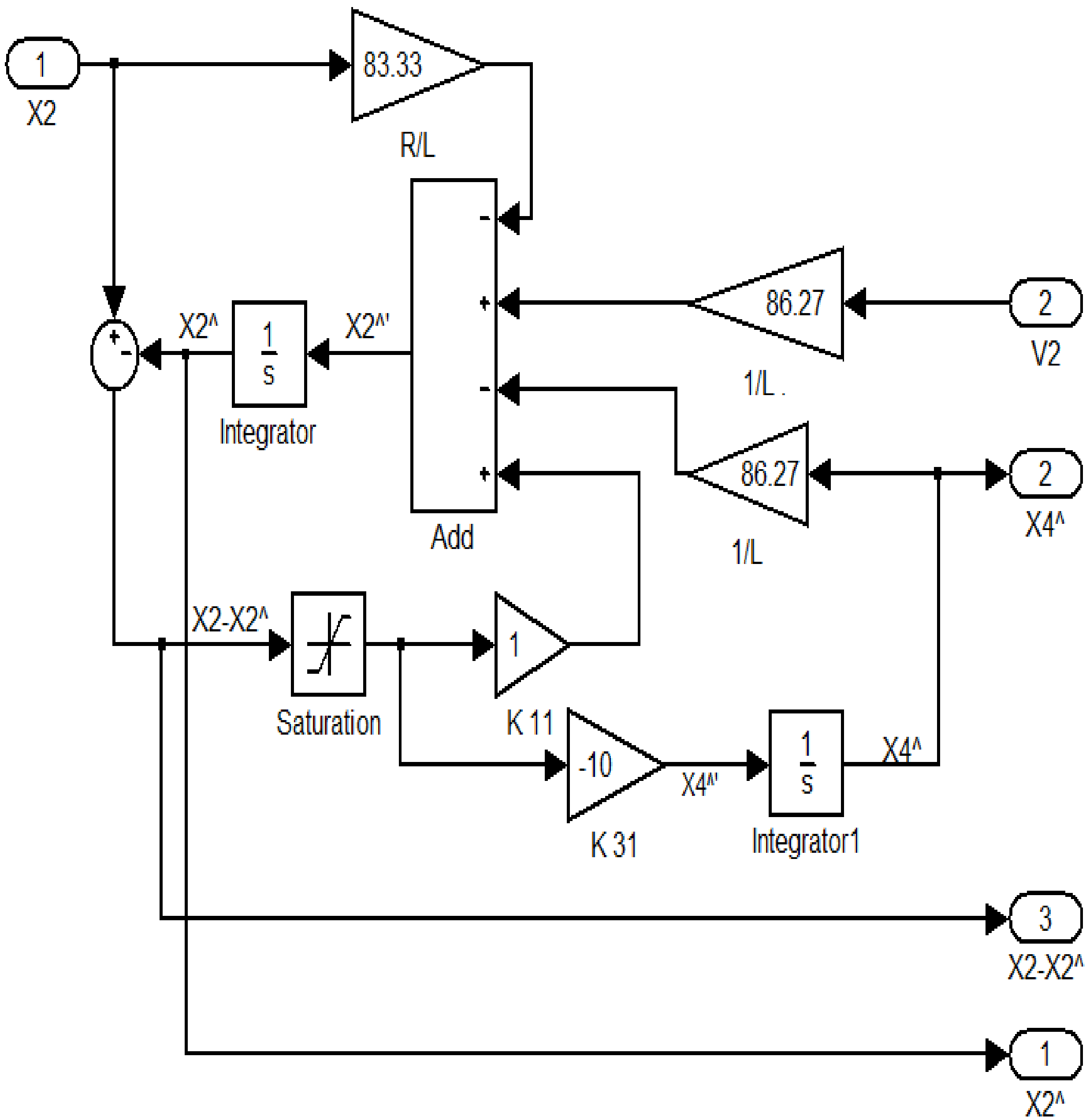

Fig. 4.4: Sliding Mode Observer for X_2

The speed of the motor is determined by using the E_{max} detection circuit which is shown in figure 4.5. This Circuit determines the value of E_{max} which is then used in eq. 3.9 to calculate the speed of the motor. The block of SMO on the output side generates the estimated phase to phase back-EMFs i.e. $\hat{E}_{ab}, \hat{E}_{bc}\ and\ \hat{E}_{ca}$. These estimated back-EMFs are then used in the generation of commutation points $(a, -a,\ b, -b,\ c\ and - c)$. The block of commutation points implemented on Simulink package is shown in figure 4.6

The commutation points triggers the inverter section and define which transistor to turn on and which transistor to turn off. The inverter is shown in figure 4.7

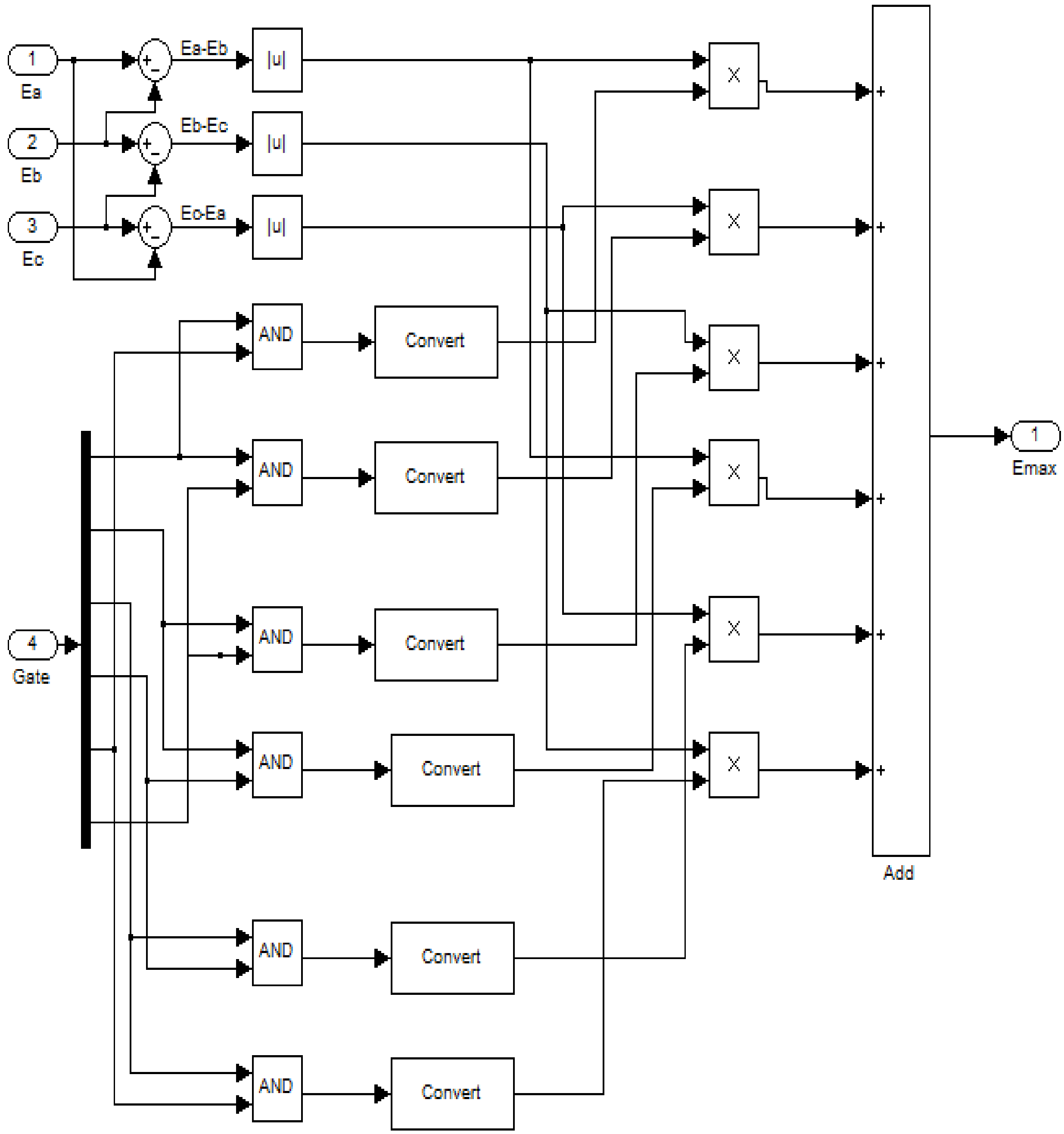

Fig. 4.5: E_{max} detection circuit

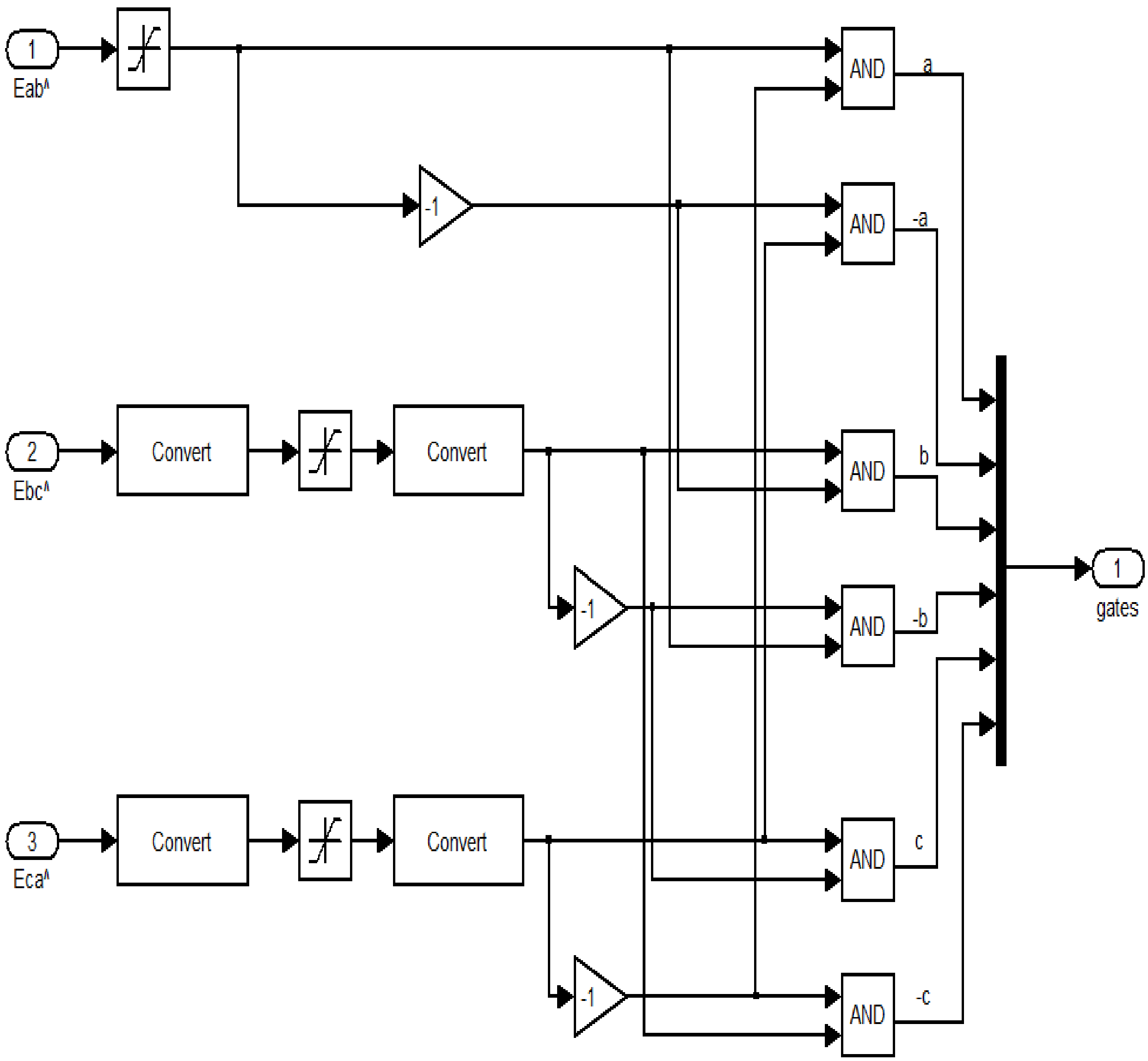

Fig 4.6: Generation of Commutation points using estimated back-EMFs

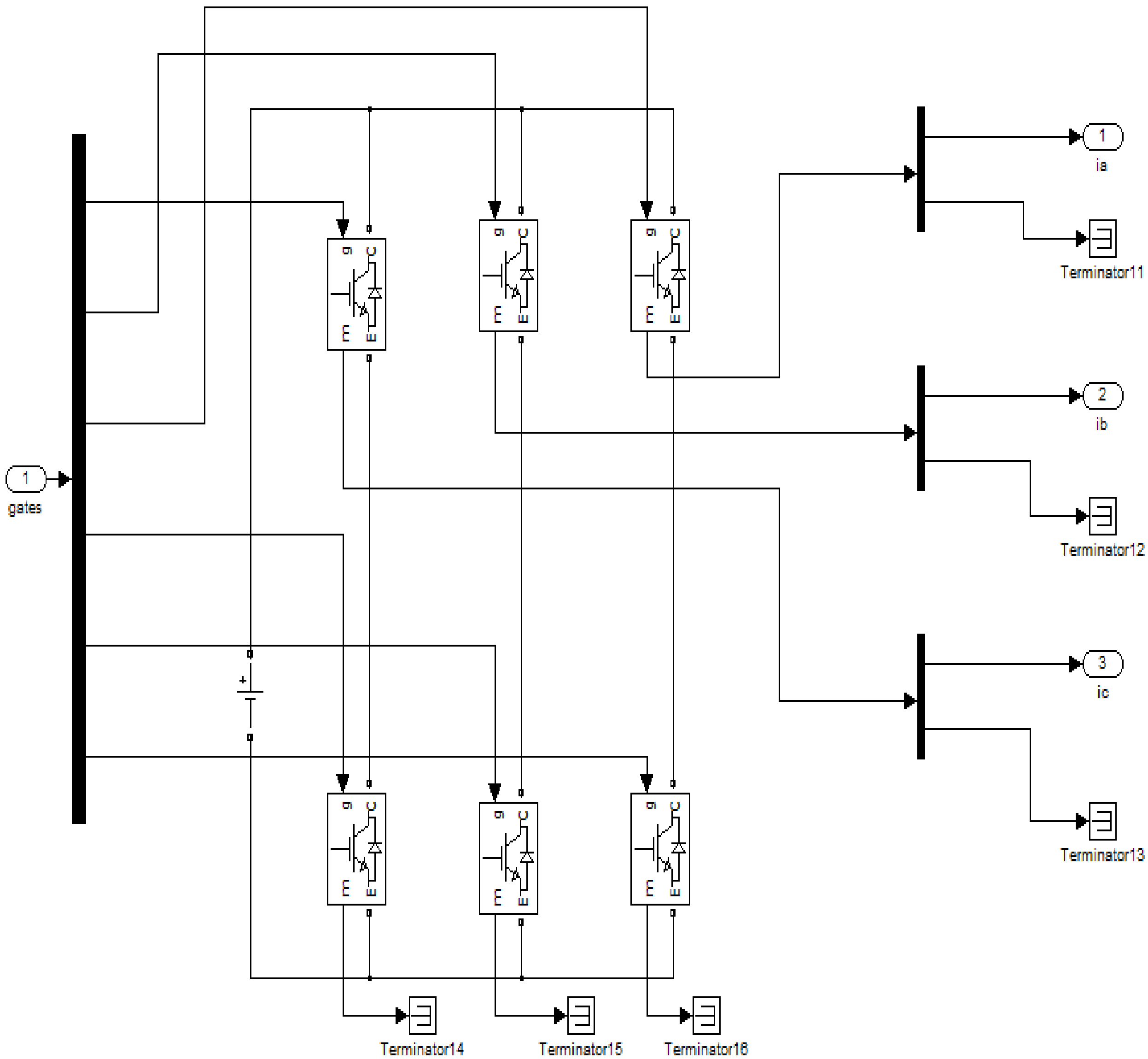

Fig. 4.7: Inverter Circuit

The comparison of actual speed of the motor ω_r and estimated speed of the motor $\widehat{\omega}_r$ is shown in figure 4.8. The reference speed of motor is set at 250 rpm and the observer has shown immediate response and settled at the reference speed at 0.02 seconds. Some minor variation is also observed but that is negligible. A similar comparison at high speed is shown in figure 4.9 where reference speed is increased to 1000 rpm i.e. $\omega_r = 1000$ rpm. Same results are shown; the observer has taken a bit longer time to settle at the higher speed which is quite obvious.

The measured speed and observed speed at $\omega_r = 1000$ rpm is shown in figure 4.10. The comparison between figure 4.9 and figure 4.10 shows that the response of SMO is better than the response of Back-EMF technique used with the Hall sensors.

The estimated back-EMF E_{ab} and E_{bc} using SMO is shown in figure 4.11 and 4.12 respectively.

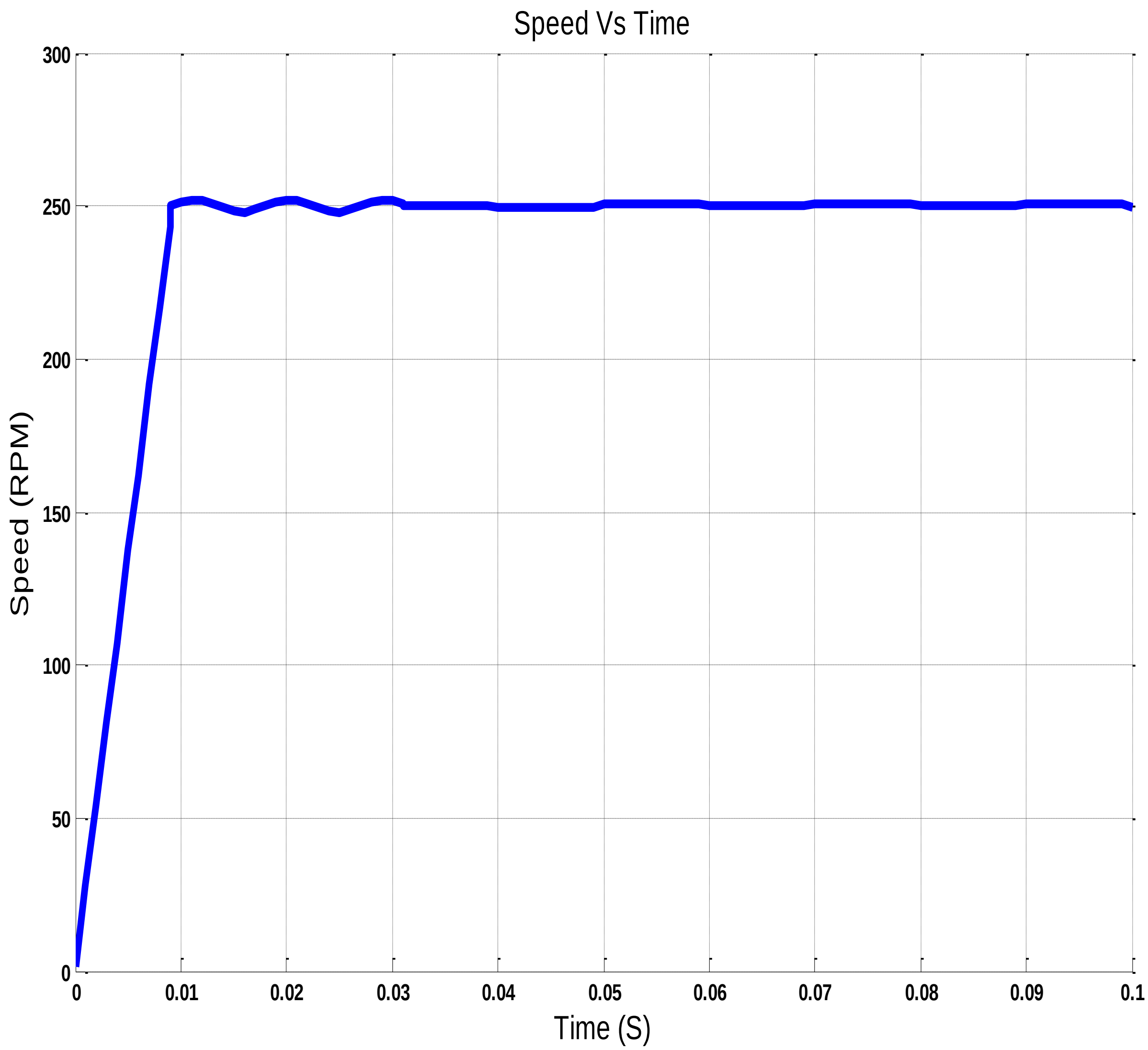

Fig. 4.8: Actual speed ω_r and estimated speed $\widehat{\omega}_r$ at $\omega_r = 250$ rpm

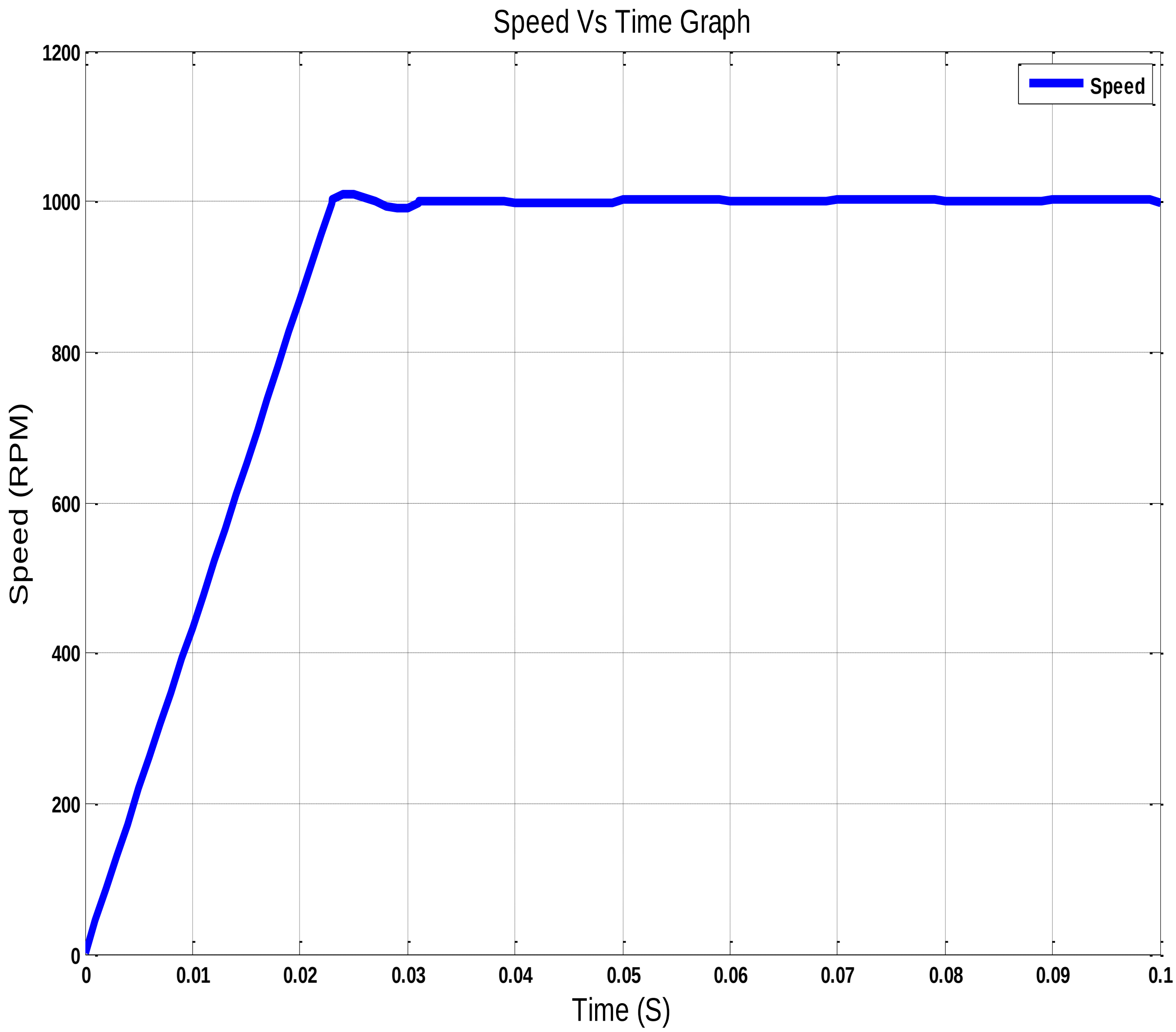

Fig. 4.9: Actual speed ω_r and estimated speed $\widehat{\omega}_r$ at $\omega_r = 1000$ rpm

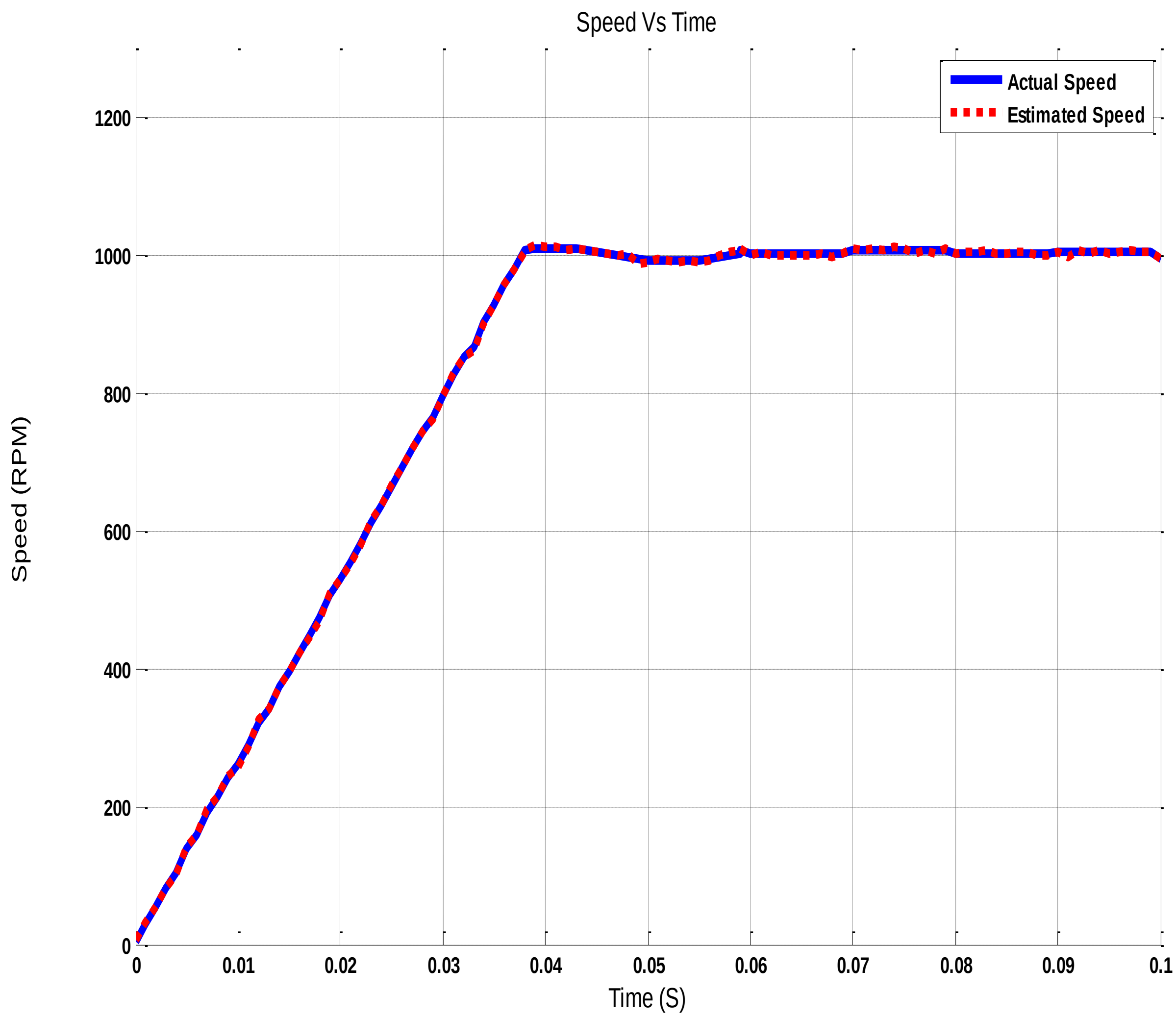

Fig. 4.10: Measured speed ω_r and estimated speed $\widehat{\omega}_r$ at $\omega_r = 1000$ rpm

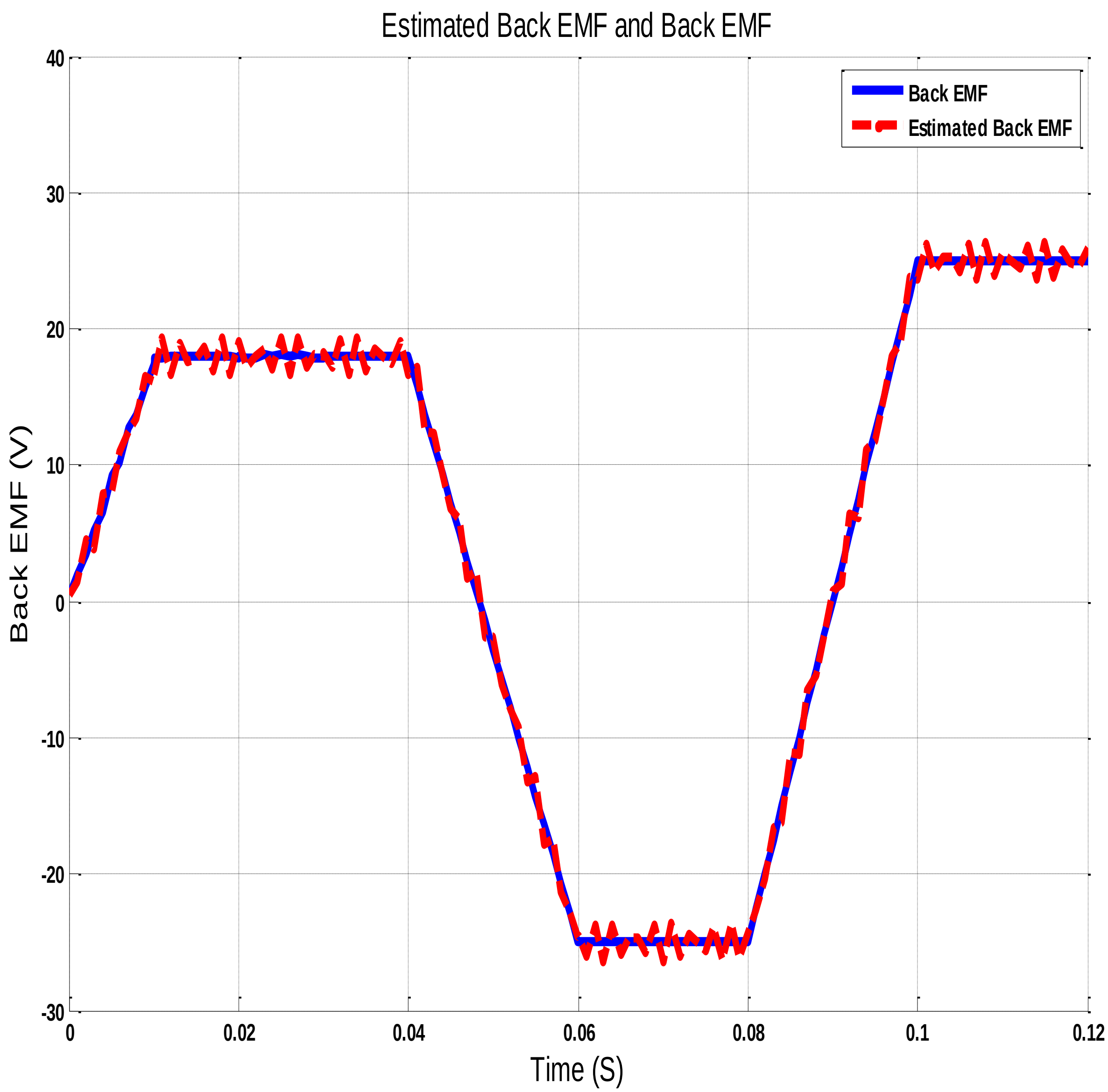

Fig. 4.11: Phase to phase back-EMF E_{ab} and observed phase to phase back-EMF $\hat{E}_{ab}$

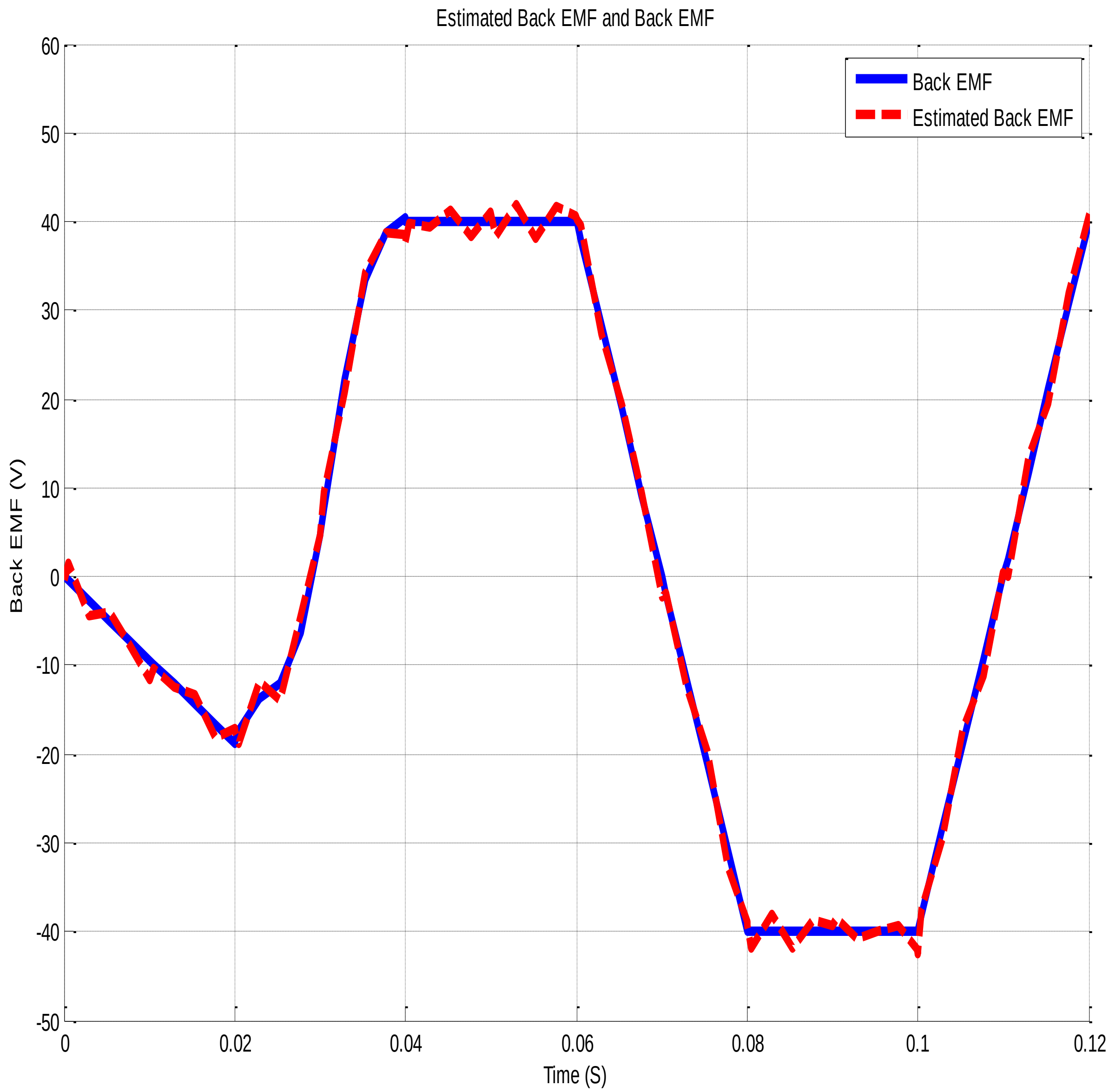

Fig. 4.12: Phase to phase back-EMF E_{bc} and observed phase to phase back-EMF $\hat{E}_{bc}$

Phase to phase back-EMF is estimated with smaller error but the only problem with the proposed SMO is the chattering issue which is catered by refining the sign function. The sign function in general, is a switching function which is replaced by a smooth and continuous sign function. This function is specially designed for smoothing the slipping surface and is defined as follows.

$$sign\,(s_i) = \begin{cases} 1 & if \quad s_i > \mu_3 \\ \frac{1-v_2}{\mu_3-\mu_2}(s_i - \mu_2) + v_2 & if \quad \mu_2 \le s_i \le \mu_3 \\ \frac{v_2-v_1}{\mu_2-\mu_1}(s_i - \mu_1) + v_1 & if \quad \mu_1 \le s_i \le \mu_2 \\ \frac{v_1-v_0}{\mu_1-\mu_0}(s_i - \mu_0) + v_0 & if \quad \mu_0 \le s_i \le \mu_1 \\ \frac{s_i}{\mu_0} & if \quad \mu_2 \le s_i \le \mu_3 \\ \frac{v_1-v_0}{\mu_1-\mu_0}(s_i + \mu_0) - v_0 & if \quad -\mu_1 \le s_i \le -\mu_0 \\ \frac{v_2-v_1}{\mu_2-\mu_1}(s_i + \mu_1) - v_1 & if \quad -\mu_2 \le s_i \le -\mu_1 \\ \frac{1-v_2}{\mu_3-\mu_2}(s_i + \mu_2) - v_2 & if \quad -\mu_3 \le s_i \le -\mu_2 \\ -1 & if \quad s_i < -\mu_3 \end{cases} \tag{4.1}$$

Where, $\mu_0 = 0.1,\ \mu_1 = 1, \mu_2 = 1.6$ and $v_0 = 0.01, v_1 = 0.5$ and $v_2 = 0.8$

The plot of sign function is shown in figure 4.13 and the modified Simulink diagram with the triggering sign function is shown in figure 4.14. Highly precise sign function has greatly reduced the chattering issue as shown in figure 4.15 and figure 4.16

The estimated back-EMFs plotted by observer with the refined sign function have shown that the performance of the observer becomes better than the previous results of estimated back-EMFs. Hence the performance of the observer has greatly improved by the mathematical variations in sign function.

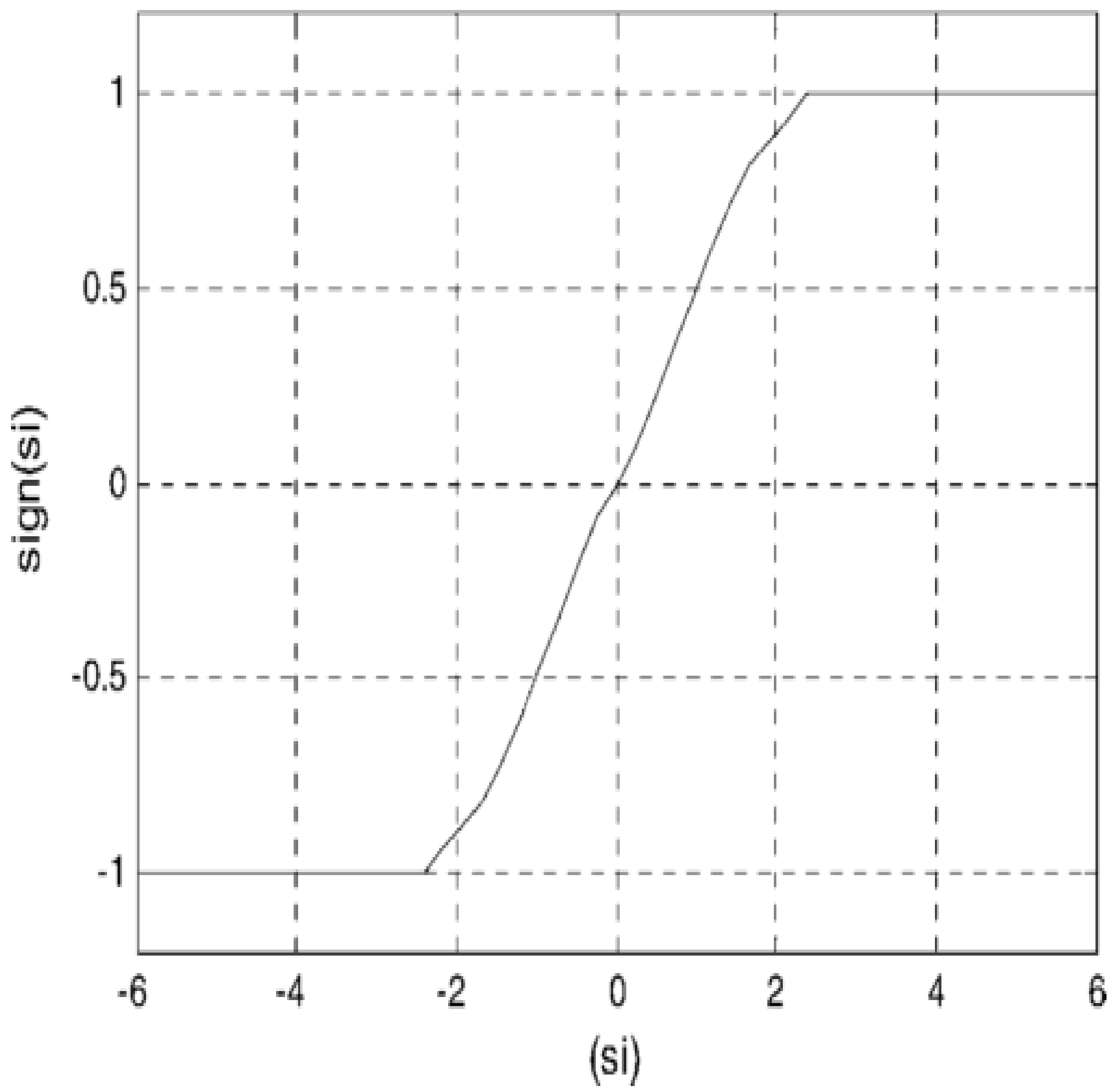

Fig. 4.13: Sign function

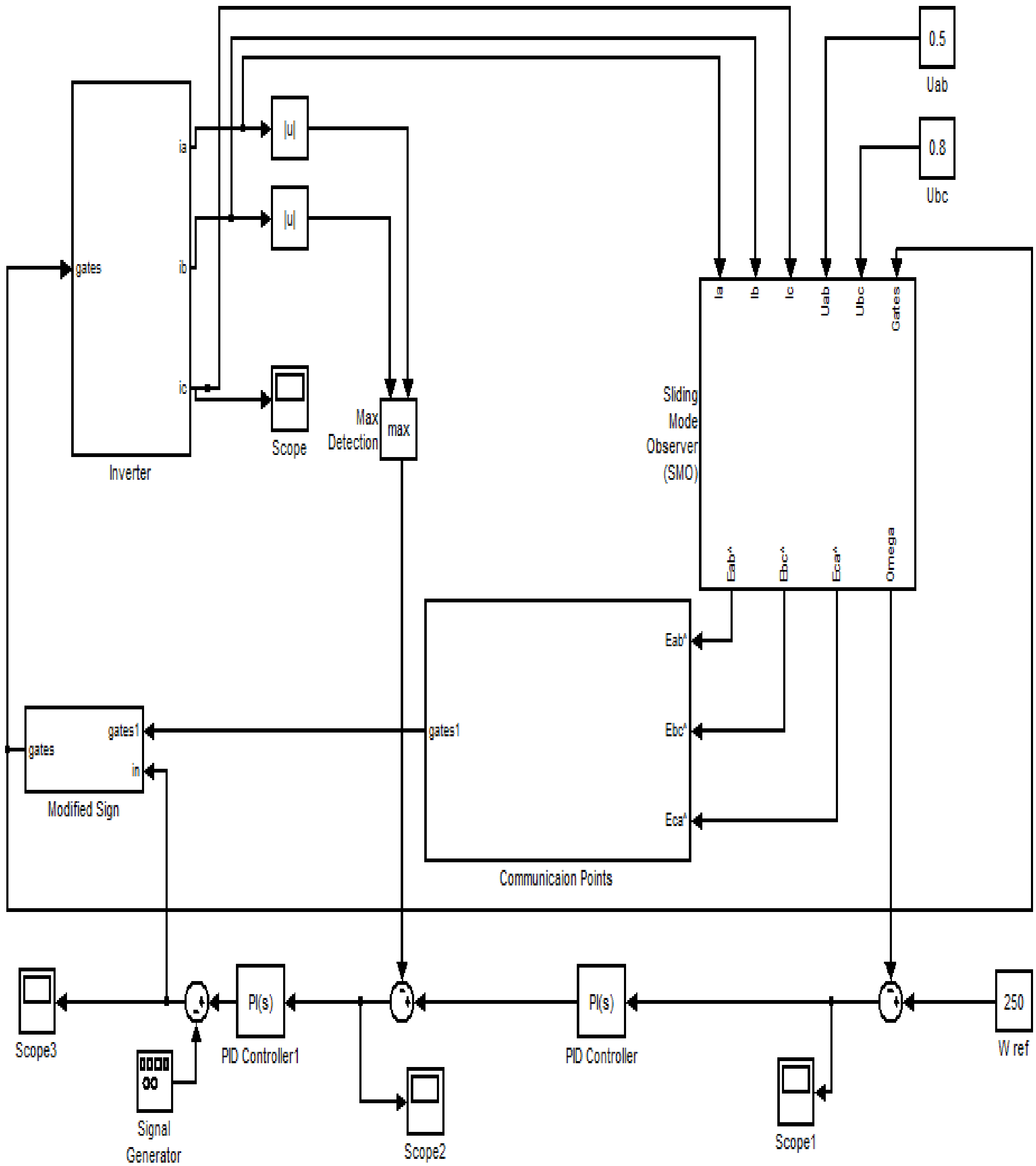

Fig. 4.14: Modified system model on Simulink

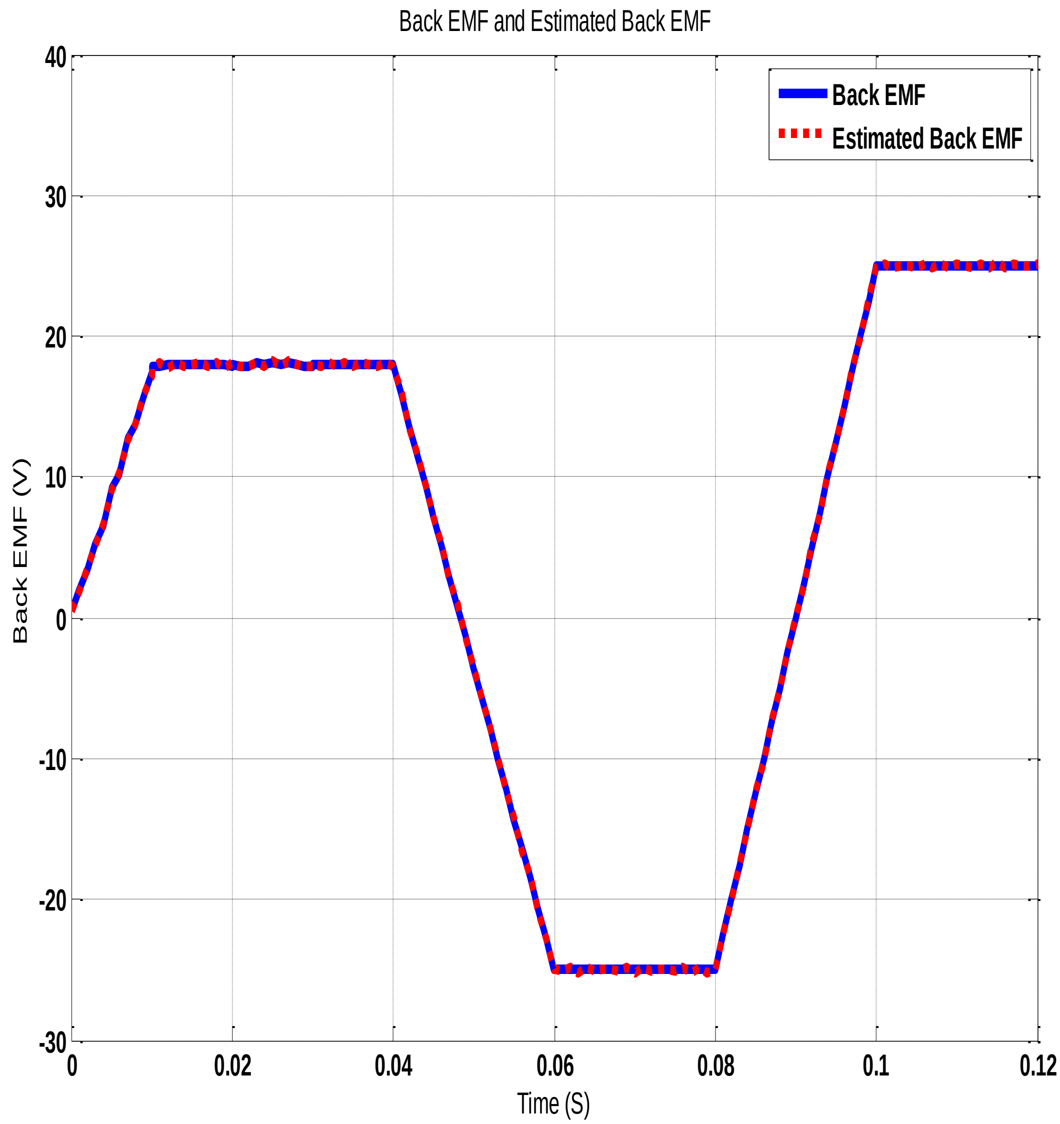

Fig. 4.15: Phase to phase back-EMF E_{ab} and observed phase to phase back-EMF $\hat{E}_{ab}$ with refined sign function

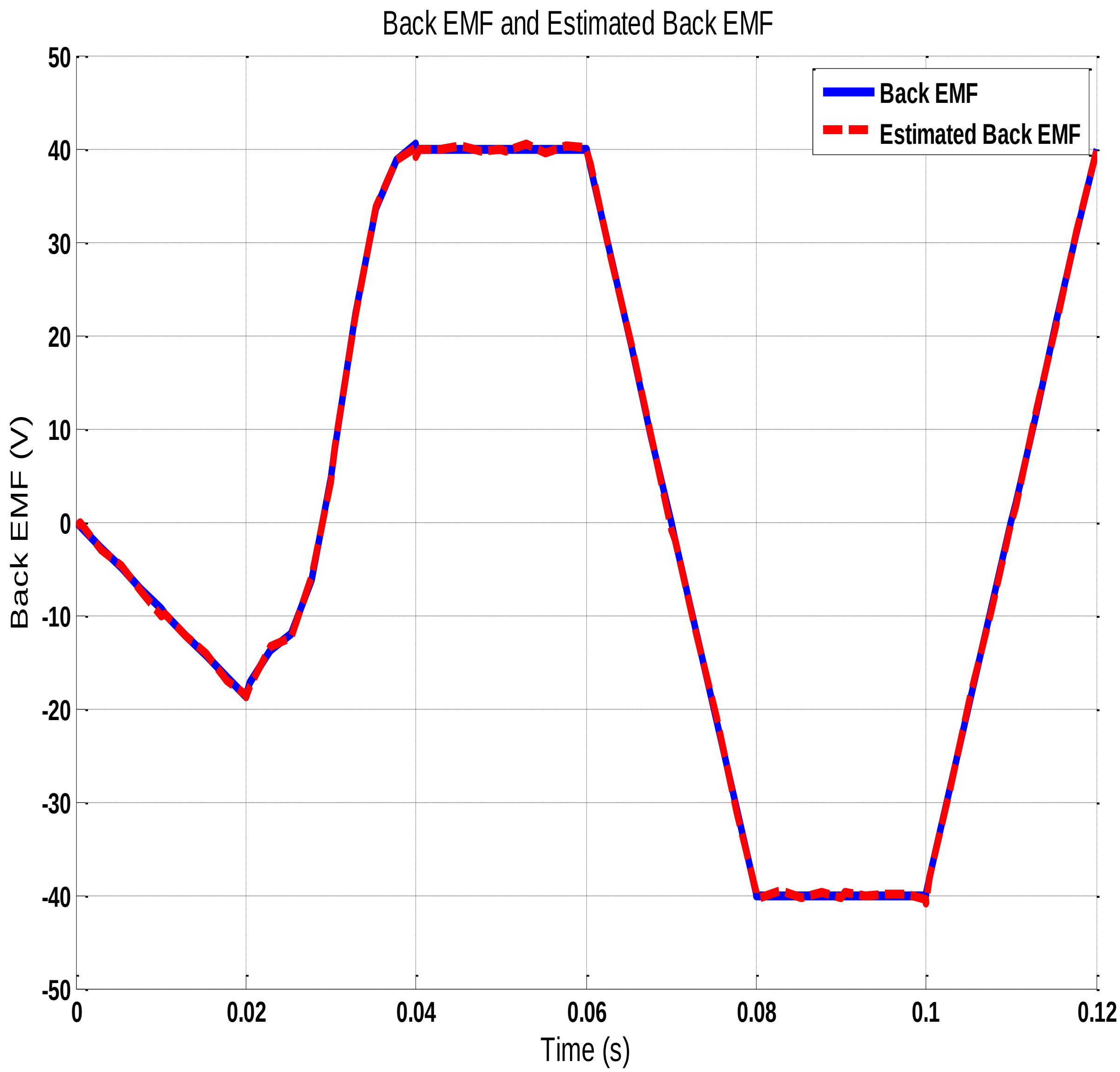

Fig. 4.16: Phase to phase back-EMF E_{bc} and observed phase to phase back-EMF $\hat{E}_{bc}$ with refined sign function

Chapter 5

5. Future course of direction of proposed system and overall conclusion

5.1 Future works

The main ideology behind this work was to devise and simulate a sensorless control technique for controlling the speed of BLDCM which could eliminate the limitations of sensors and add some reliability in to the system. The proposed scheme has modified the design of SMO which has improved the performance as well, but the challenges which are still out of the scope of this work and the limitations would be considered as future enhancements. Following areas of improvements and future directions are proposed:

1. A physical set-up may be established for the practical implementation of the proposed system.

2. Performance of the current system can be evaluated by implementing high gain observers in place of SMO. A comparative study with both observers could be conducted.

3. Some other sensorless control techniques like EKF and MRAS could be implemented.

4. The current system can be further evaluated for improvements by making it adaptive.

These are the future prospects which could be implemented to further improve this work. This work presents a preliminary structure, which aims at developing a control technique for speed control of BLDC motor and this structure can be improved by implementing above future prospects.

5.2 Conclusion

In this work, a brief insight regarding the established methods for speed controlling of BLDC motor is presented along with the practical implementation of Sliding Mode Observer. It is evident from this study that the methods which uses position sensors for speed controlling of BLDCM can be further improved by eliminating the position sensors which would not just reduces the cost but also increases the reliability. Some applications demand higher reliability and performance and in some applications the installation of position sensors in not possible due to harsh environmental conditions, hence the sensorless control is the only solution to cater these requirements. Sliding mode control is a unique and emerging sensorless control technique, which is used for the speed control of BLDC motor.

In this thesis, SMO design is proposed which estimates the trapezoidal back-EMF of BLDCM which in turn determines the speed of the motor using mathematical relationship between back-EMF and rotor speed. The simulation of proposed observer shows that the SMO is robust, it provides good estimate of back-EMFs, and it also caters the chattering problem of SMO.

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