Design, Development and Implementation of Controller For The Wheel Hub BLDC Motor in an Electric Scooter

A Report Submitted in Partial Fulfilment of the Requirements for the Degree

of

MASTER OF TECHNOLOGY

by

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Chapter 1

1 Introduction

Brushless dc (BLDC) motors are recommended for many low- and medium-power drives applications because of their high efficiency, high flux density per unit volume, low maintenance requirement, low electromagnetic interference (EMI) problems, high ruggedness, and a wide range of speed control. Due to these advantages, they find applications in numerous areas such as household application, transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning, motion control and robotics, renewable energy applications etc. The BLDC motor is a three-phase synchronous motor consisting of a stator having a three-phase concentrated windings and a rotor having permanent magnets. It does not have mechanical brushes and commutator assembly; hence, wear and tear of the brushes and sparking issues as in case of conventional dc machines are eliminated in BLDC motor and thus it has low EMI problems. This motor is also referred as an electronically commutated motor since an electronic commutation based on the Hall-effect rotor position signals is used rather than a mechanical commutation.

Permanent magnet motors with trapezoidal back EMF (120°conduction mode) and sinusoidal back EMF (180°conduction mode) have several advantages over other motor types. Most notably, (compared to dc motors) they are lower maintenance due to the elimination of the mechanical commutator and they have a high-power density which makes them ideal for high torque- to weight ratio applications. Compared to induction machines, they have lower inertia allowing for faster dynamic response to reference commands. Also, they are more efficient due to the permanent magnets which results in virtually zero rotor losses. Permanent magnet brushless dc (PMBLDC) motors could become serious competitors to the induction motor for servo applications.

The PMBLDC motor is becoming popular in various applications because of its high efficiency, high power factor, high torque, simple control and lower maintenance . The major disadvantage with permanent magnet motors is their higher cost and relatively higher complexity introduced by the power electronic converter used to drive them. The added complexity is evident in the development of a torque/speed regulator. The magnetization directions and intensities are analyzed using finite element analysis with a detailed magnetization procedure for ferrite bonded magnets used in inner-rotor type BLDC motors.

1.1 General block diagram of open loop simulation of BLDC motor

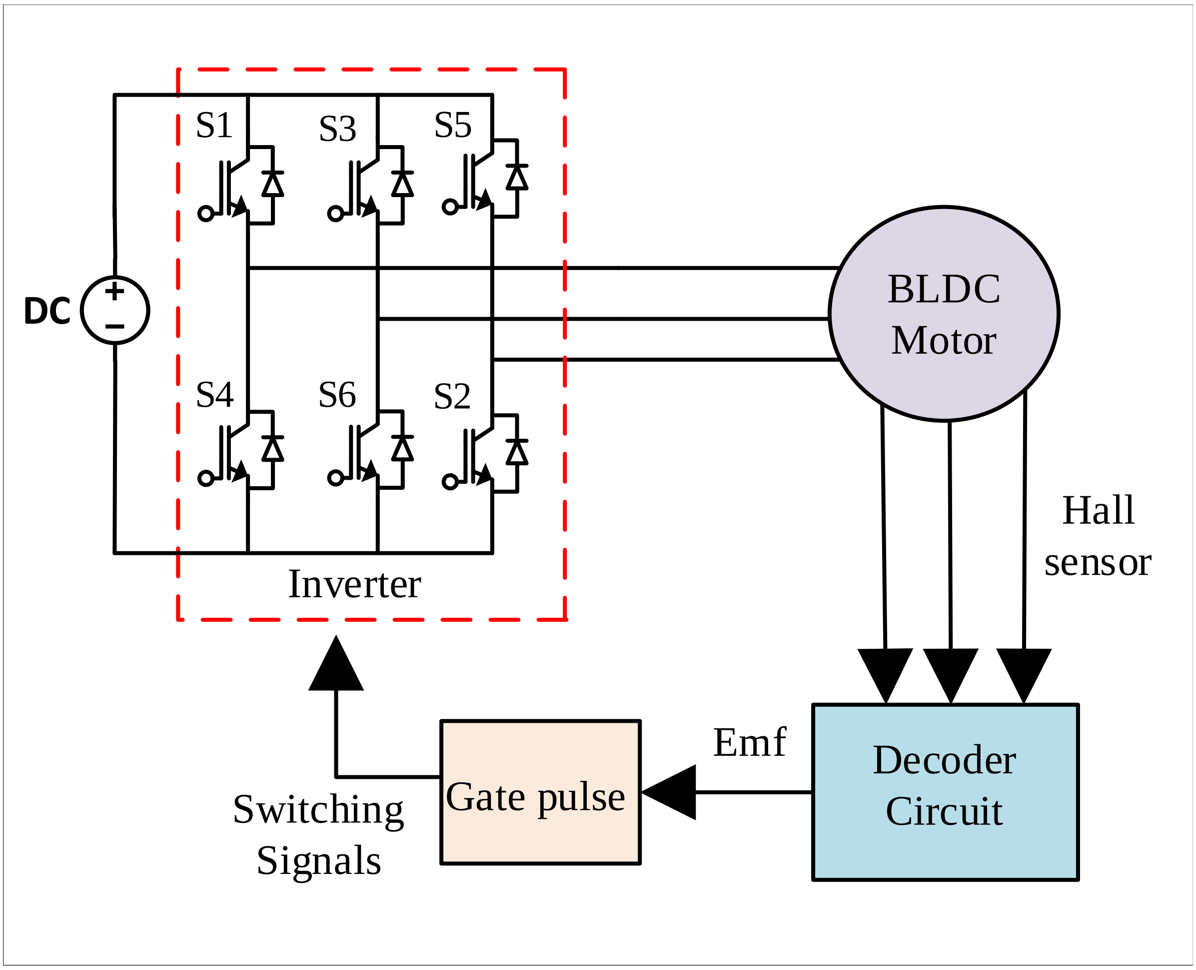


Fig. 1: General block diagram of open loop operation of BLDC motor

2 120°conduction mode

To drive Brushless dc motor, each coil of conventional 120 degree commutation rotates only 120°with current to generate torque, and wait for next excitation in the other 60°without torque generated.

In the case of 120 degree commutation, the current flow of three phases is shown in fig 2. Phase A and B are conducted in this conduction interval, however the phase C is unconnected with neither high nor low side of the inverter. Each modulation is of 60 degree, which is 1/6 of electrical period. Each winding is conducted "on" for 120 degree.

So at a particular instant only two switches are operating at a time that means at any instant only two phase will be operating and the third phase will be floating. The third phase will wait till next instant to come.

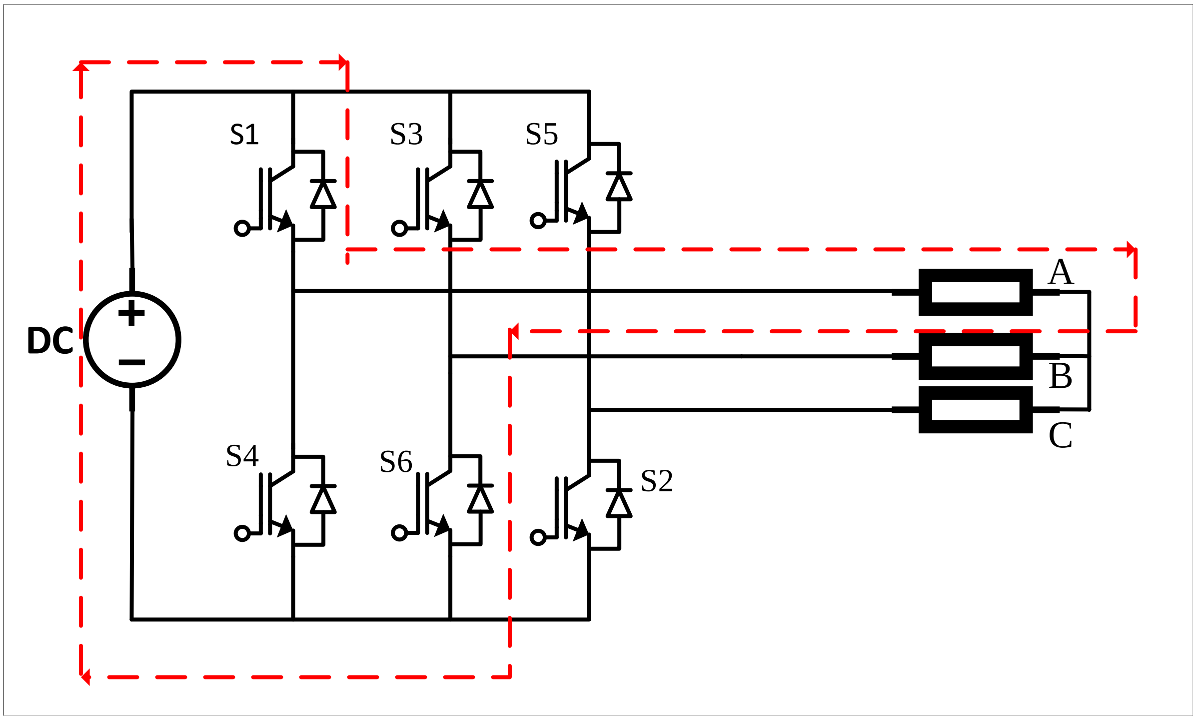
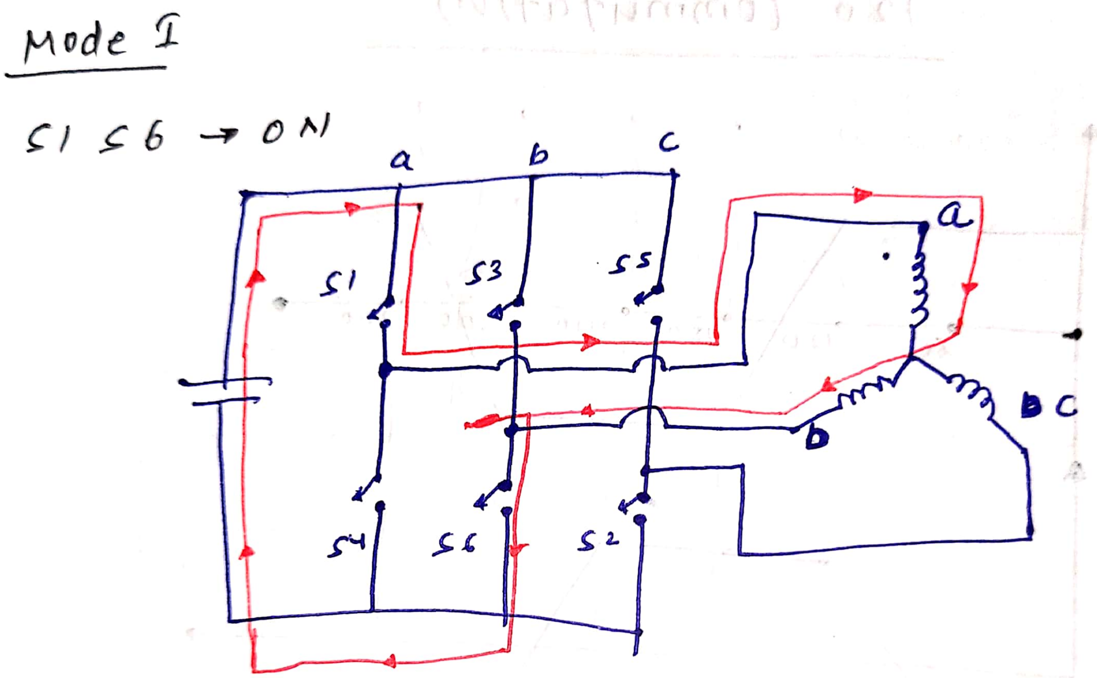


Fig. 2: Flow of current in three windings for 120°commutation

2.1 Different modes of operation in 120 degree commutation



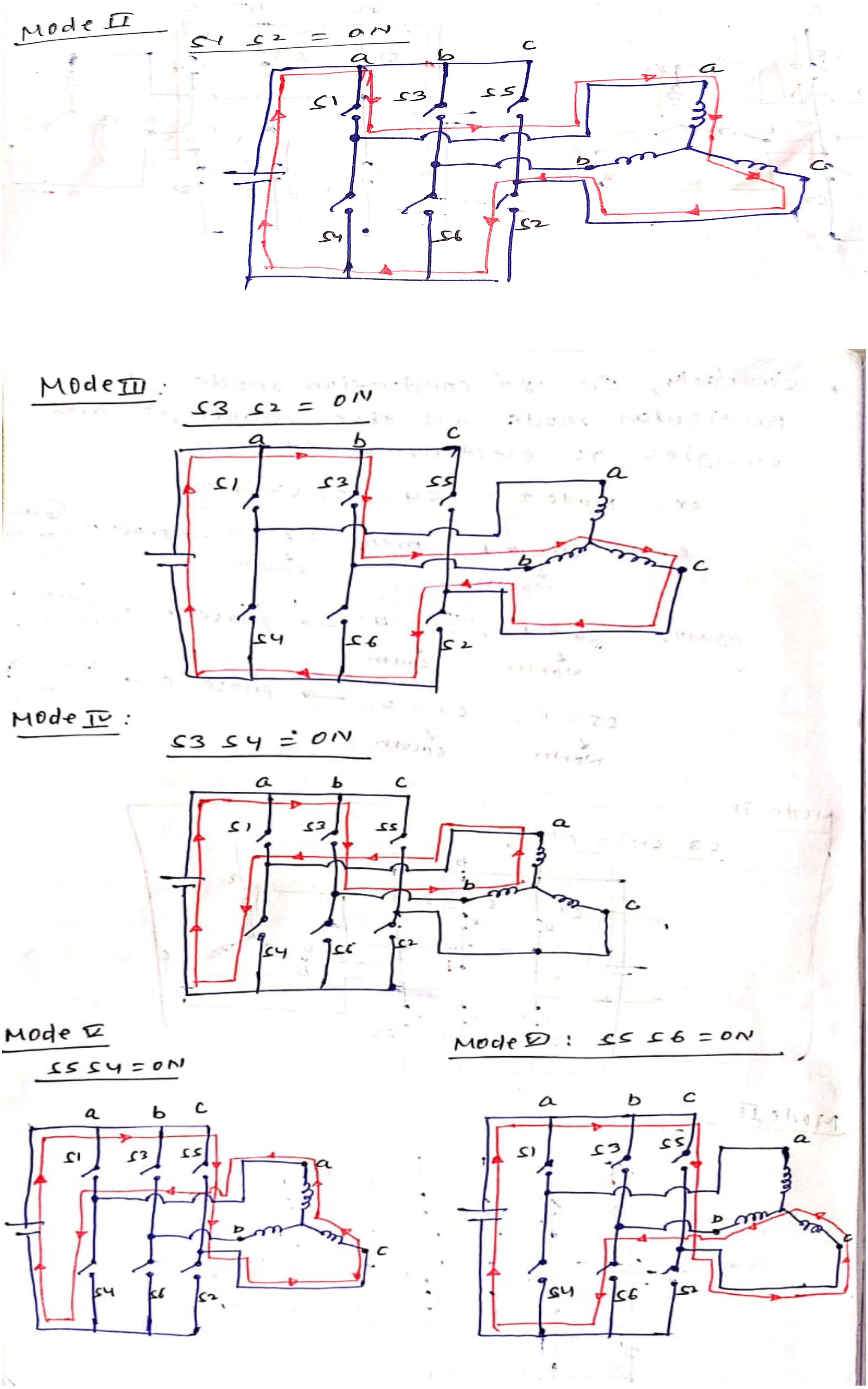


Fig. 3: All six modes of operation in 120-degree commutation

2.2 Switching logic of 120 degree commutation mode

	60°	120°	180°	240°	300°	360°
S1	S1	S1				
S2		S2	S2			
S3			S3	S3		
S4				S4	S4	
S5					S5	S5
S6	S6					S6
	S1S6	S1S2	S2S3	S3S4	S4S5	S5S6

Fig. 4: Switching logic of 120°commutation

2.3 Truth table of 120 degree commutation mode

Mode	Hall A	Hall B	Hall C	emf A	emf B	emf C	S1	S2	S3	S4	S5	S6
I	1	0	1	+1	-1	0	1	0	0	0	0	1
II	1	0	0	+1	0	-1	1	1	0	0	0	0
III	1	1	0	0	+1	-1	0	1	1	0	0	0
IV	0	1	0	-1	+1	0	0	0	1	1	0	0
V	0	1	1	-1	0	+1	0	0	0	1	1	0
VI	0	0	1	0	-1	+1	0	0	0	0	1	1

Where,

- Ha, Hb and Hc are the signals coming from hall effect sensors.
- Ea, Eb and Ec are the back emf enduced in the motor.
- S1, S2, S3, S4, S5 and S6 are the switches of the inverter.

2.4 Boolean expression of different switches

From the above truth table, after simplifying we get the following simplified boolean expressions for all switches:

- $S1 = Ha\,\overline{H}b$
- $S3 = Hb\,\overline{H}c$
- $S5 = Hc\,\overline{H}a$
- $S4 = \overline{H}aHb$
- $S6 = \overline{H}bHc$
- $S2 = \overline{H}cHa$

2.5 Decoder and Switching diagram

By the help of above simplified boolean expressions we can design decoder circuit which can perform the 120°conduction operation.

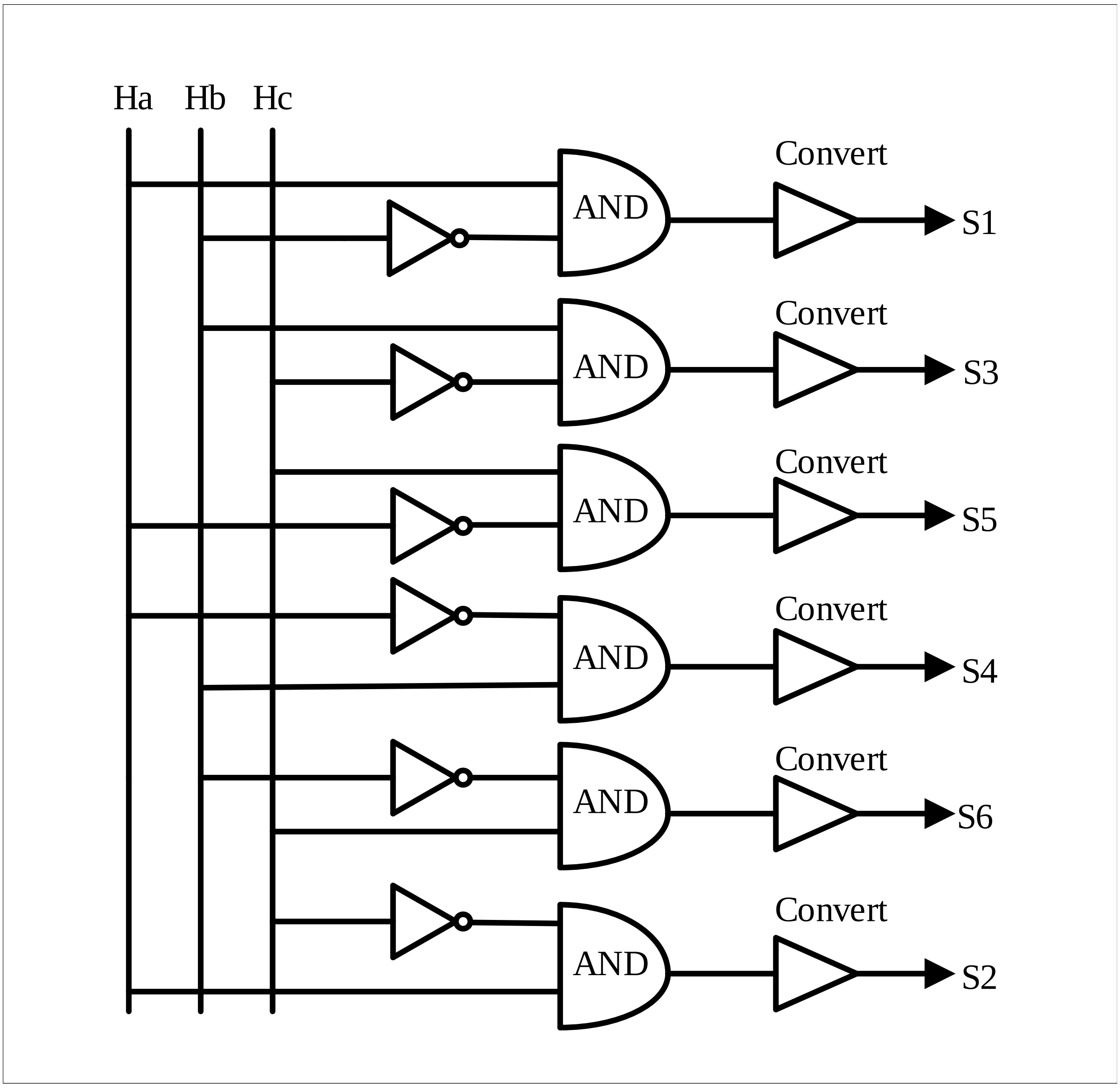


Fig. 5: Decoder and Switching diagram of 120°commutation

2.6 Analysis for different modes

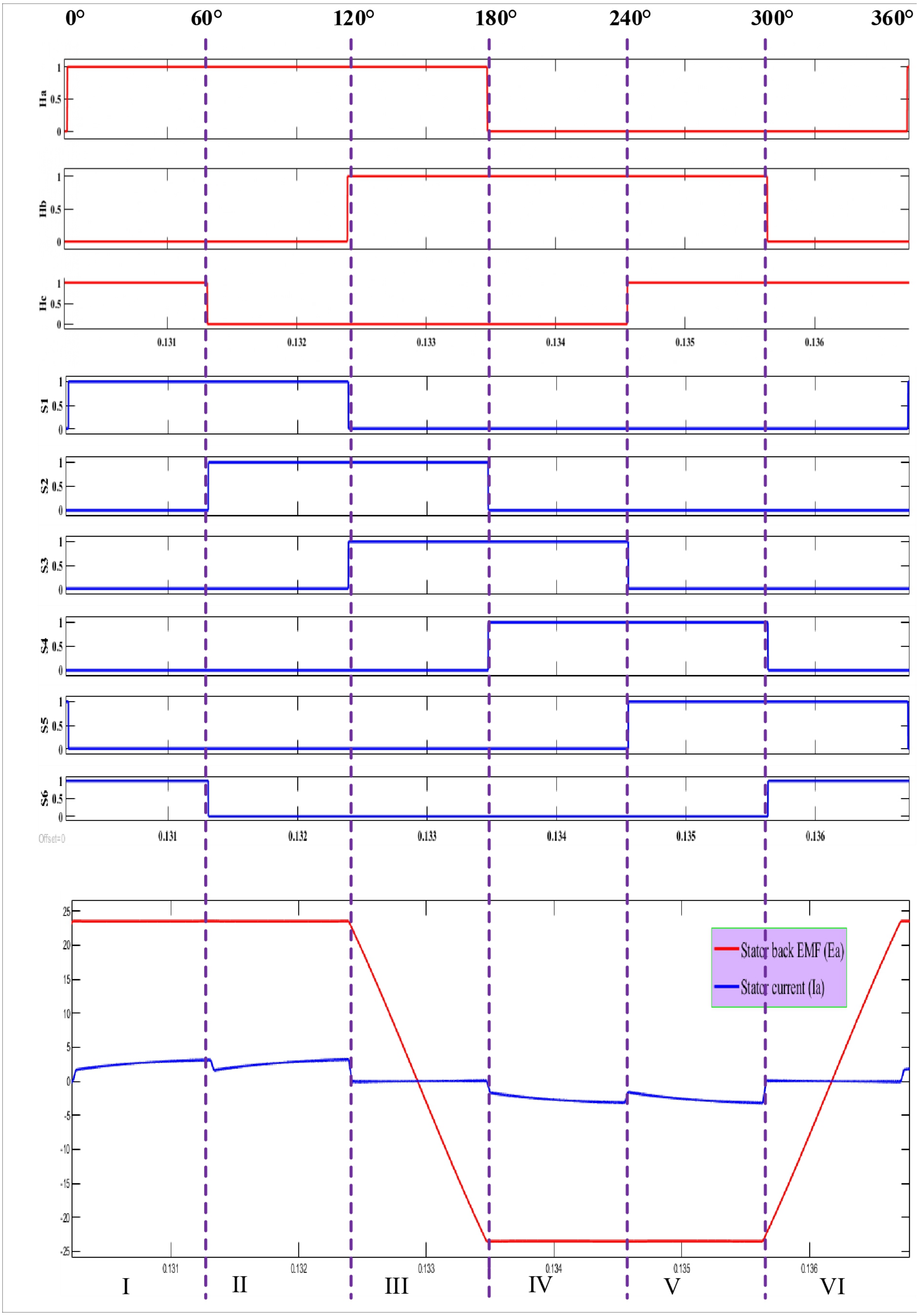


Fig. 6: Hall signals, Switching signals, Stator back EMF and stator current

3 180°conduction mode

The 180-degree commutation can be realized as a three-phase-drive model, which means that all of the three phases are conducted with current to generate torque in each of the conduction intervals. Theoretically, 180-degree commutation system is expected to generate greater maximum torque comparing to the conventional 120-degree commutation.

Each coil of 180-degree commutation works for the entire electrical period, which is expected to deliver more power. 180-degree commutation is conducted “on” of 180 degree of each phase. Three-phase current flow of 180-degree commutation is shown in fig 7.

So at a partular instant three switches are operating at a time that means there will be no any phase will be floating in any instant. This is the main difference in 120-degree and 180-degree conduction mode, because in 120-degree conduction mode, at any instant only two phase will be operating and the thr third phase will be floating.

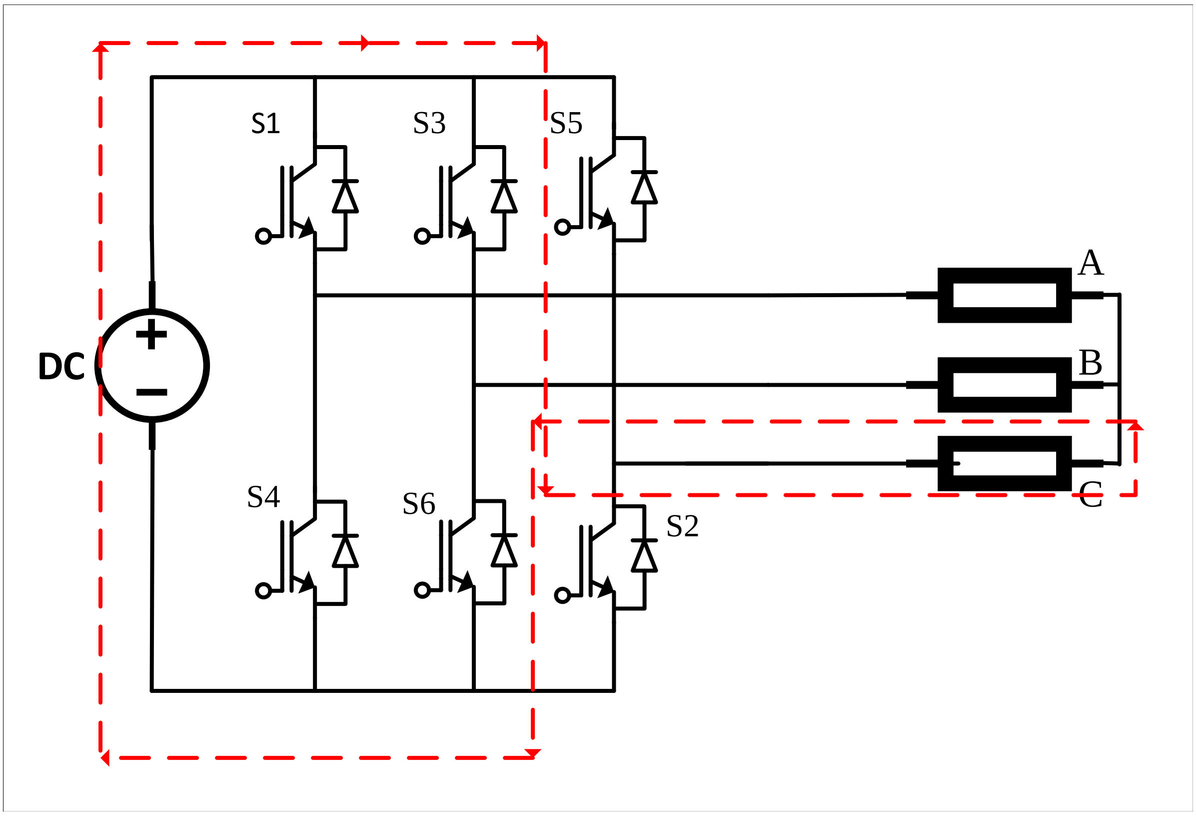


Fig. 7: Flow of current in three windings for 180°commutation

3.1 Different modes of operation in 180-degree commutation

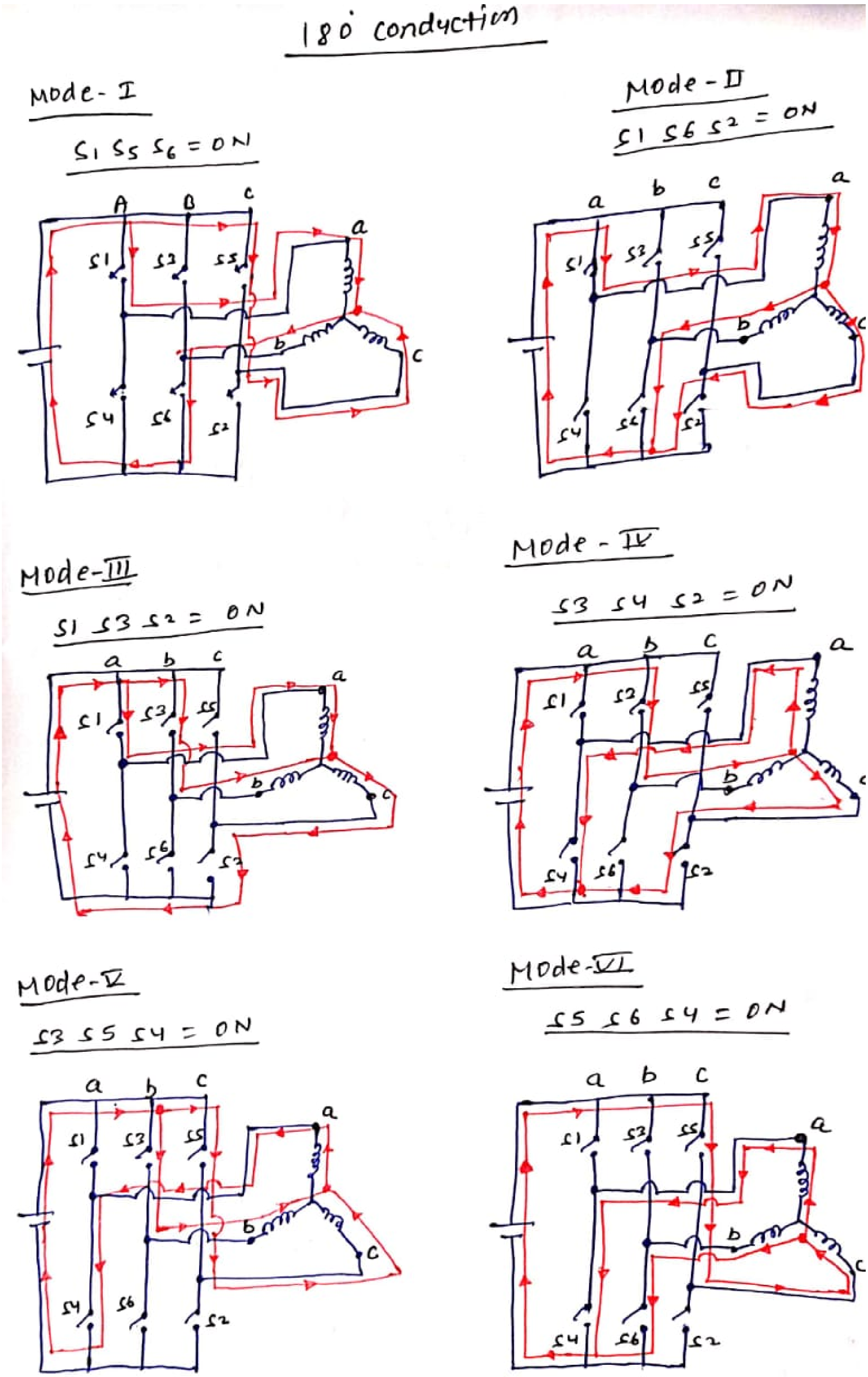


Fig. 8: All six modes of operation in 180°commutation

3.2 Switching logic of 180 degree commutation mode

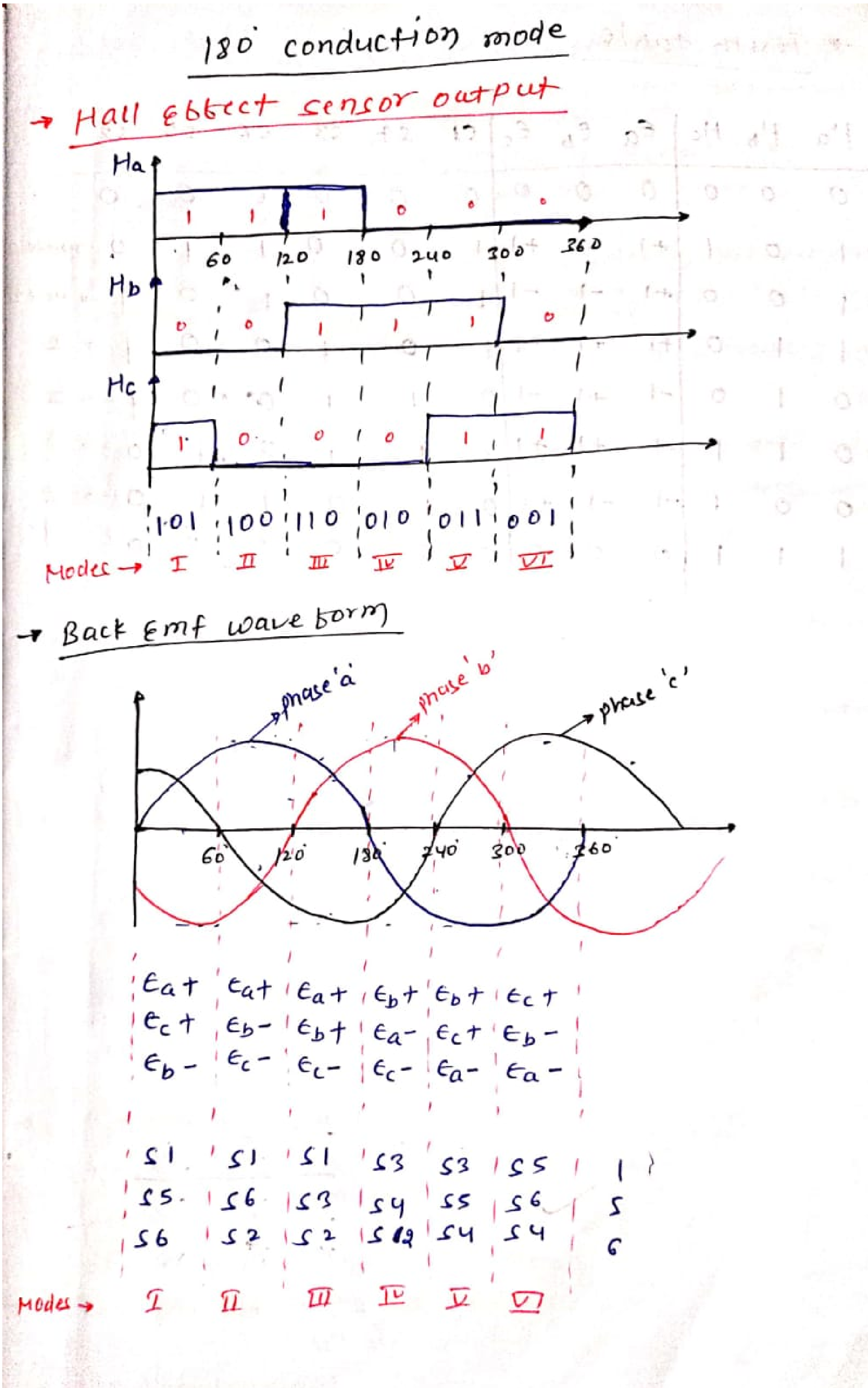


Fig. 9: Switching logic of 180°commutation

3.3 Truth table of 180 degree commutation mode

Mode	Hall A	Hall B	Hall C	emf A	emf B	emf C	S1	S2	S3	S4	S5	S6
I	1	0	1	+1	-1	+1	1	0	0	0	1	1
II	1	0	0	+1	-1	-1	1	1	0	0	0	1
III	1	1	0	+1	+1	-1	1	1	1	0	0	0
IV	0	1	0	-1	+1	-1	0	1	1	1	0	0
V	0	1	1	-1	+1	+1	0	0	1	1	1	0
VI	0	0	1	-1	-1	+1	0	0	0	1	1	1

Where,

- Ha, Hb and Hc are the signals coming from hall effect sensors.
- Ea, Eb and Ec are the back emf enduced in the motor.
- S1, S2, S3, S4, S5 and S6 are the switches of the inverter.

3.4 Boolean expression of different switches

From the above truth table, after simplifying we get the following simplified boolean expressions for all switches:

- $S1 = Ha(\overline{H}b + \overline{H}c)$
- $S3 = Hb(\overline{H}a + \overline{H}c)$
- $S5 = Hc(\overline{H}a + \overline{H}b)$
- $S4 = \overline{H}a(Hb + Hc)$
- $S6 = \overline{H}b(Ha + Hc)$
- $S2 = \overline{H}c(Ha + Hb)$

3.5 Decoder and Switching diagram

By the help to above simplified boolean expressions we can design decoder circuit which can perform the 180°conduction operation.

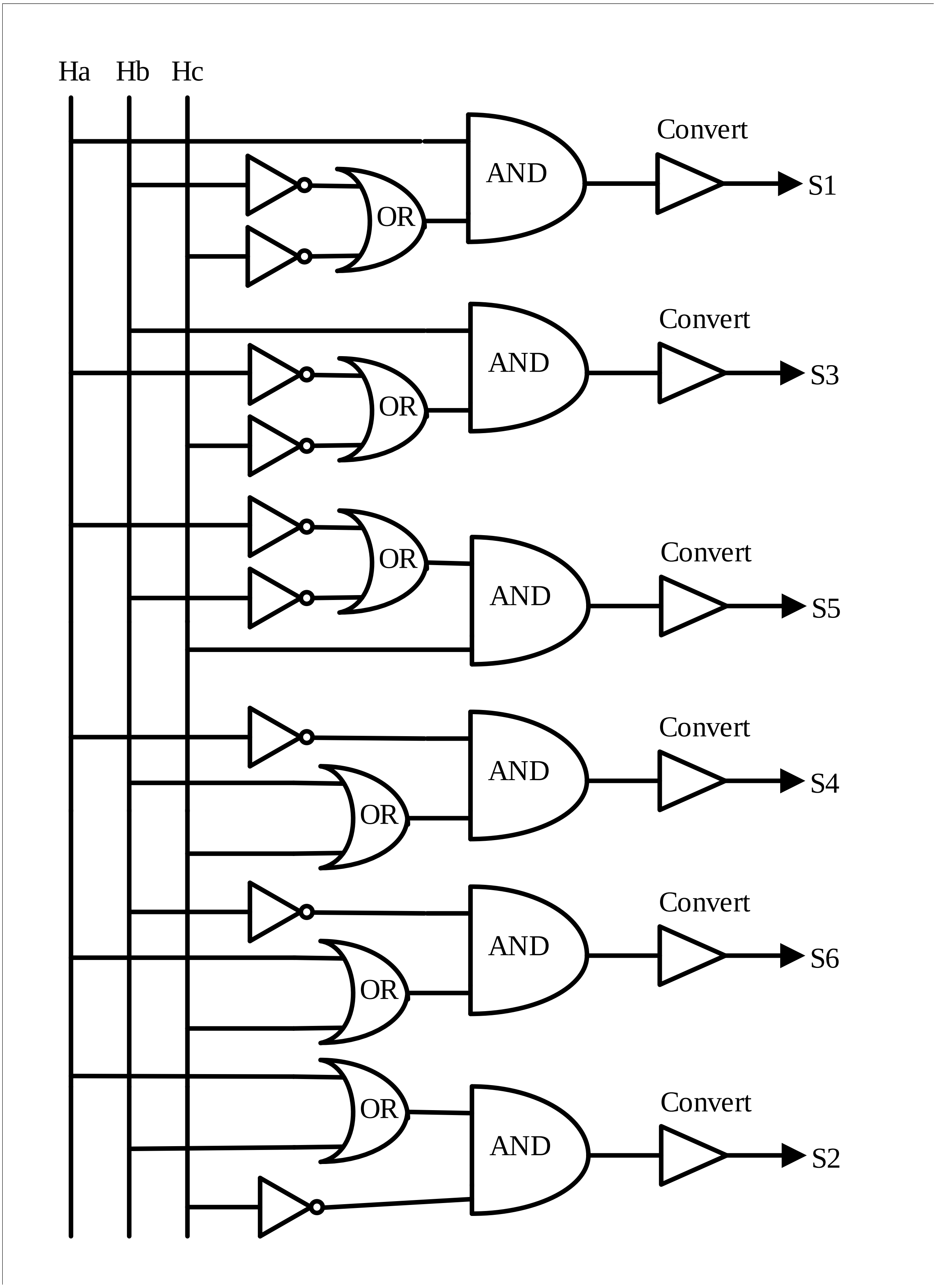


Fig. 10: Decoder and switching diagram of 180°commutation

3.6 Analysis for different modes

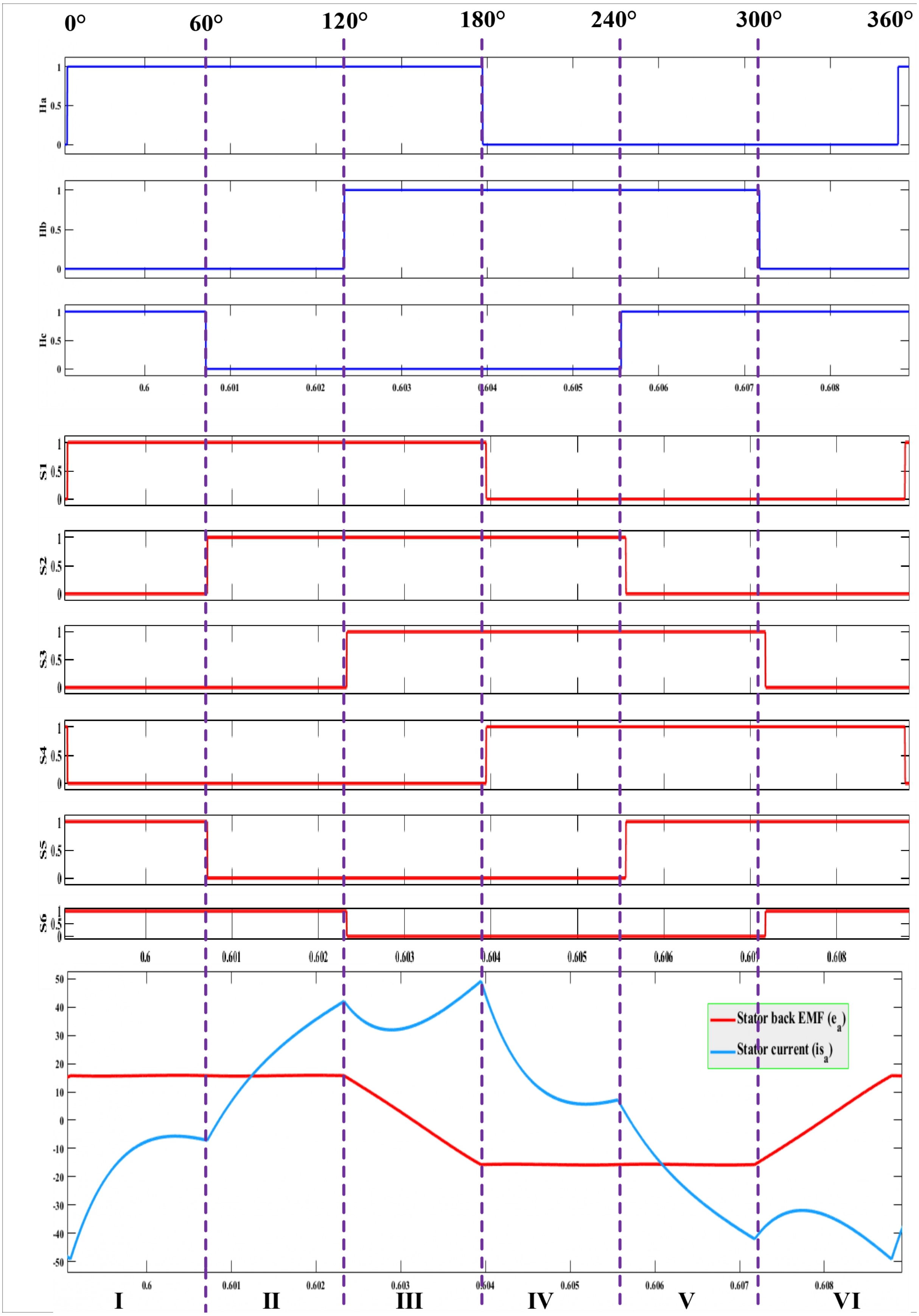


Fig. 11: Hall signals, Switching signals, Stator back EMF and stator current

Chapter 2

1 Open loop simulation of BLDC motor

In open loop simulation, we are running BLDC motor without any controller. Electronic commutation is done to get rotor position.

To get the control over speed and torque we are also also implementing pulse width modulation technique along with open loop simulation. In this we are giving a fixed duty ration and for this duty ratio we are generating modulating signal and then this signals are given to switches of inverter. we are using AND gate to combine the effect of electronic commutation as well as PWM.

1.1 General block diagram of open loop simulation of BLDC motor

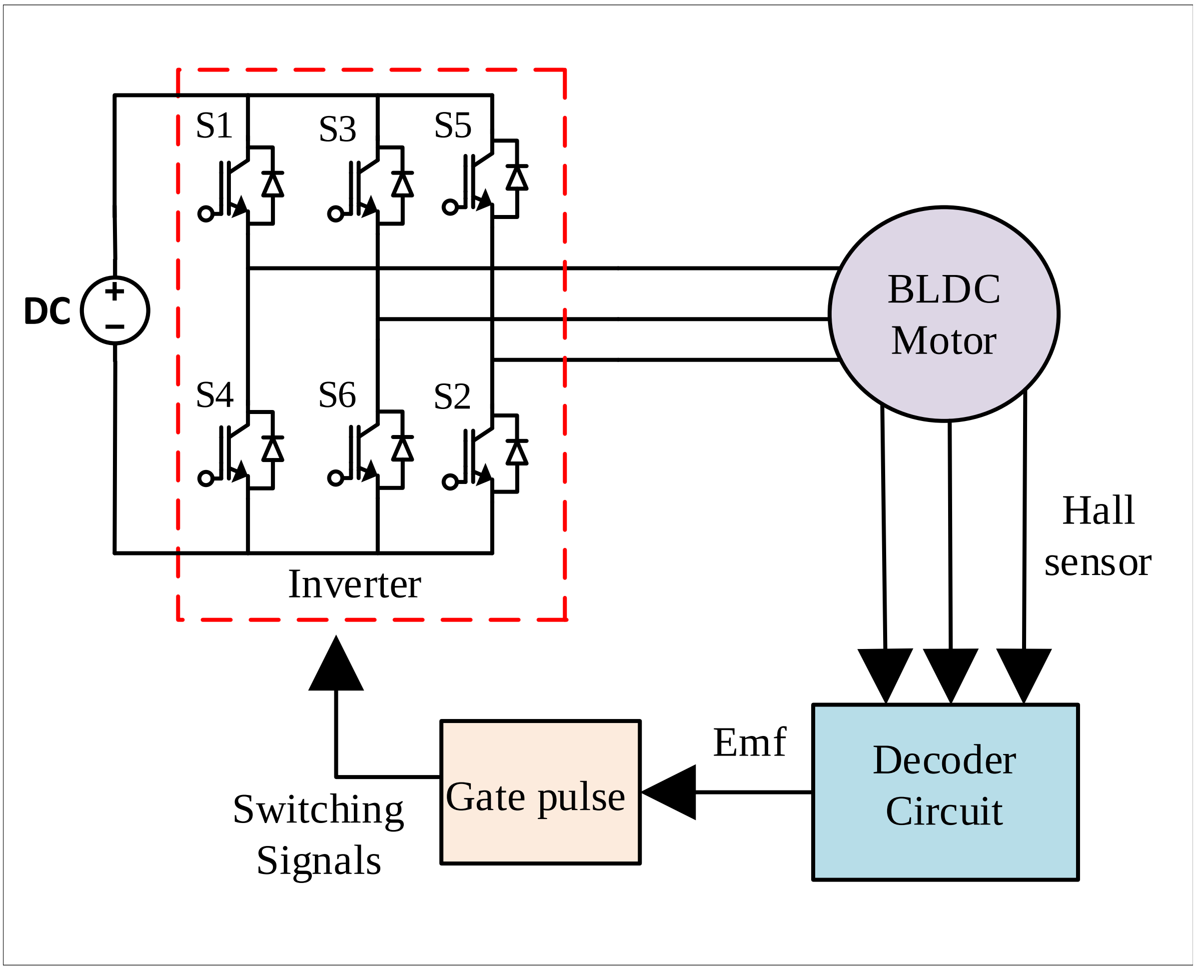


Fig. 1: General block diagram of open loop operation of BLDC motor

2 120°conduction mode

2.1 Simulation diagram

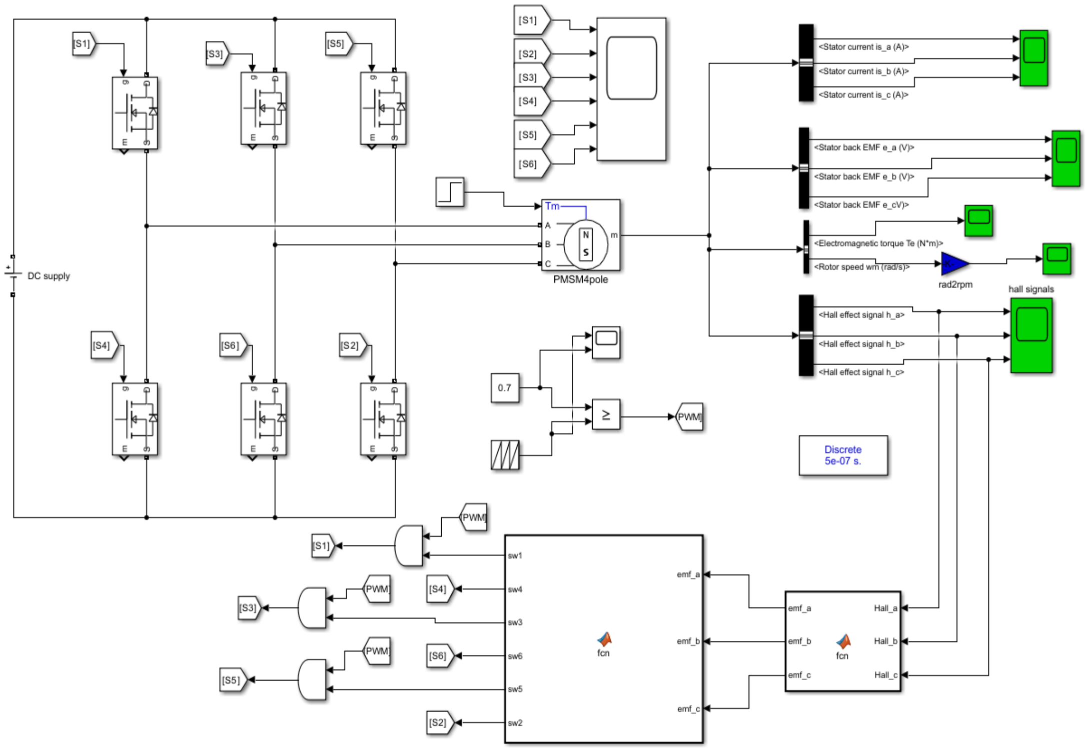
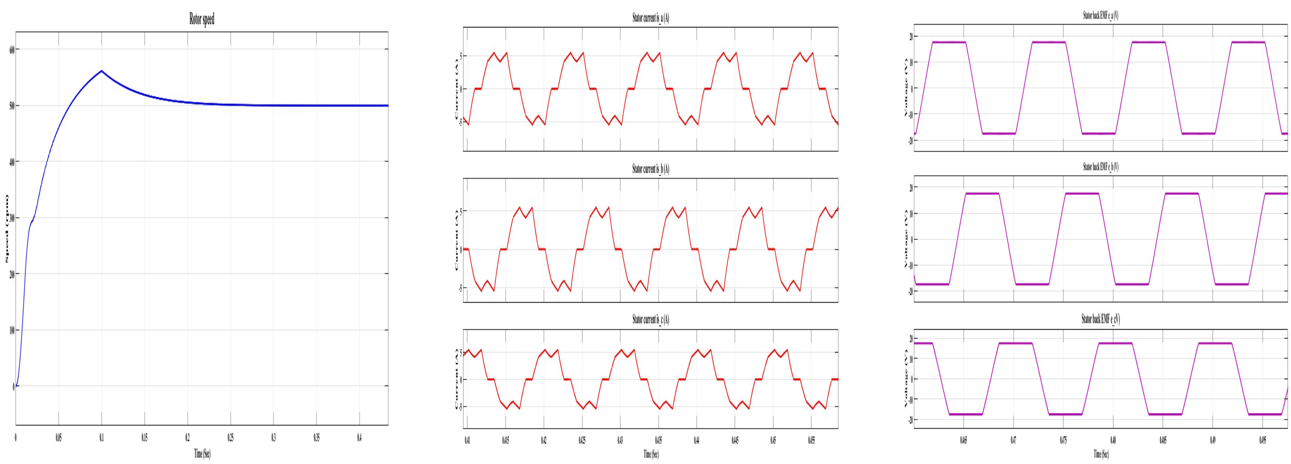


Fig. 2: Close loop simulation diagram of 120°commutation

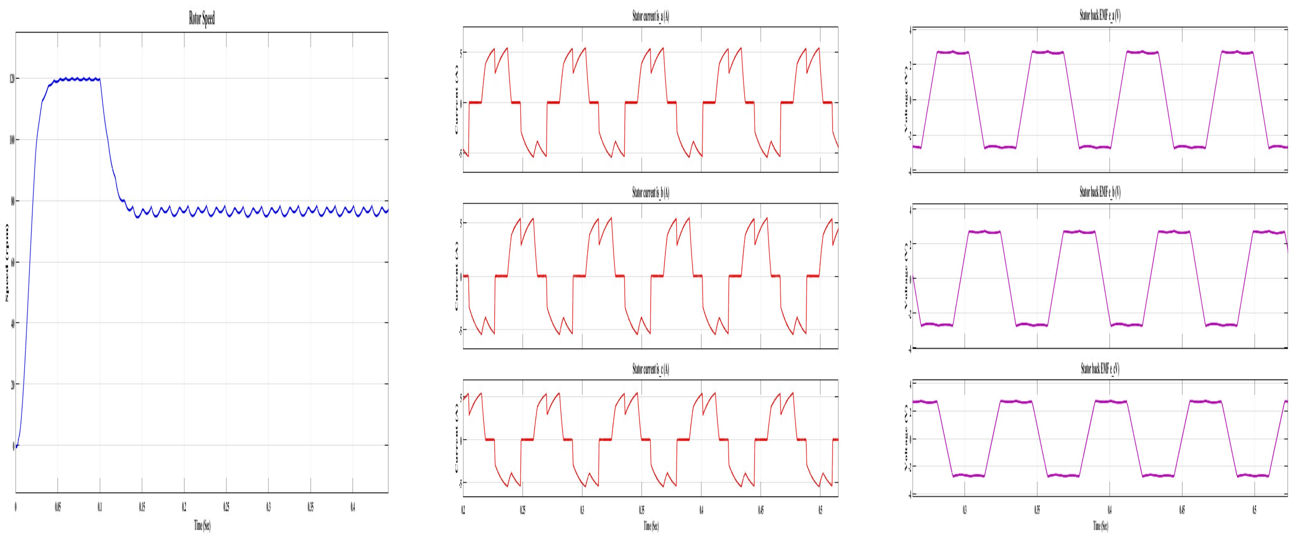
2.2 No PWm



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 3: Waveform of Rotor speed, stator current and back emf when there is no PWM technique applied

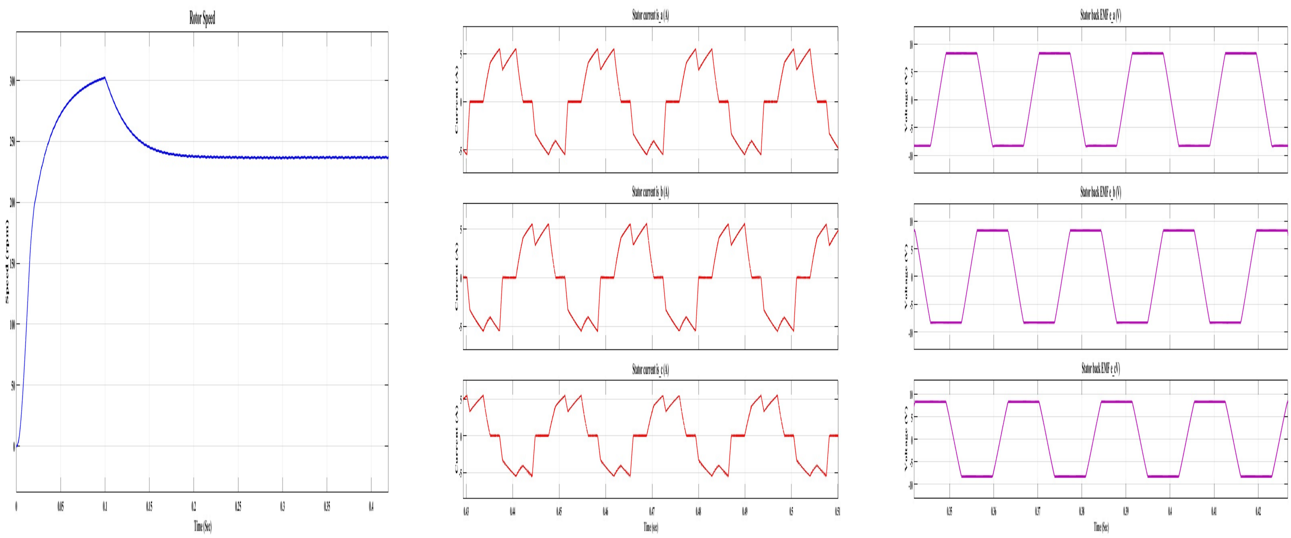
2.3 0.2 PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 4: Waveform of Rotor speed, stator current and back emf when there is PWM technique with duty ratio of 0.2 is applied

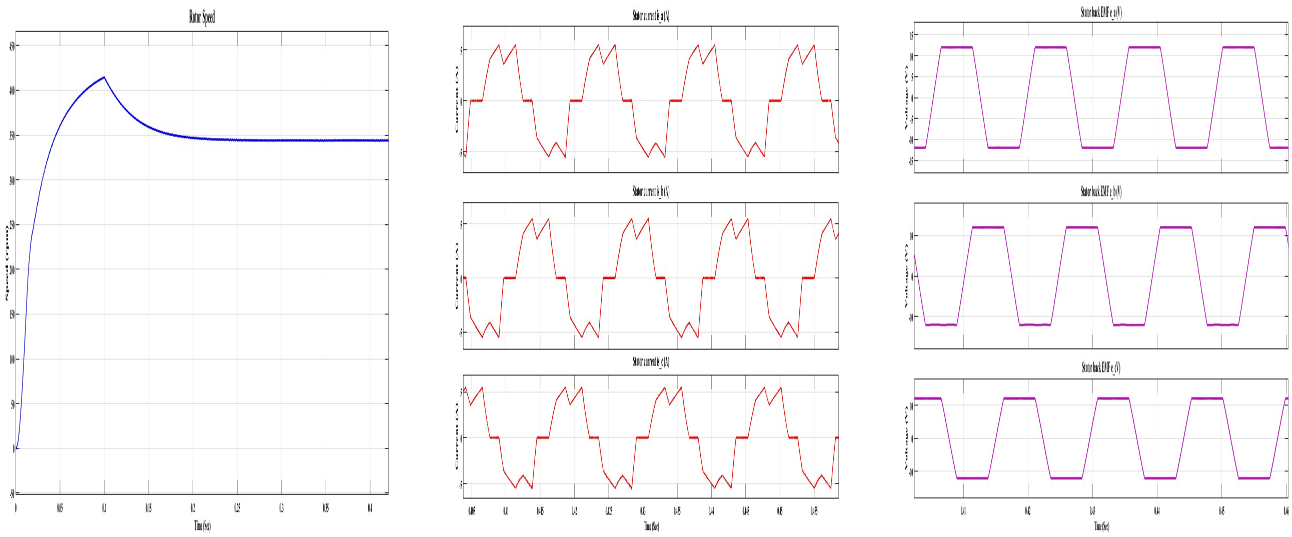
2.4 0.5 PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 5: Waveform of Rotor speed, stator current and back emf when there is PWM technique with duty ratio of 0.5 is applied

2.5 0.7 PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 6: Waveform of Rotor speed, stator current and back emf when there is PWM technique with duty ratio of 0.7 is applied

2.6 Observation

- We are getting maximum speed as well as very less ripple in speed and current when operating in the No PWM mode. But there is no variation in speed.
- As duty ratio of PWM increase speed of the motor increase.
- With PWM we have more control over range of speeds.

3 180°conduction mode

3.1 Simulation diagram

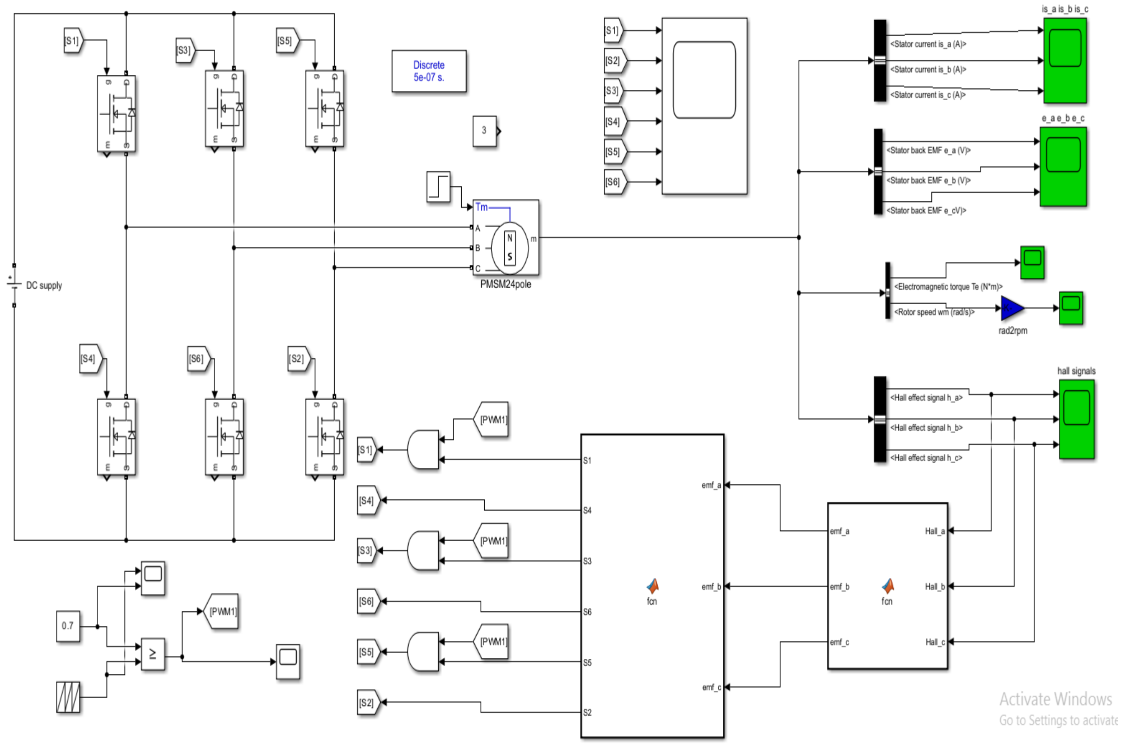
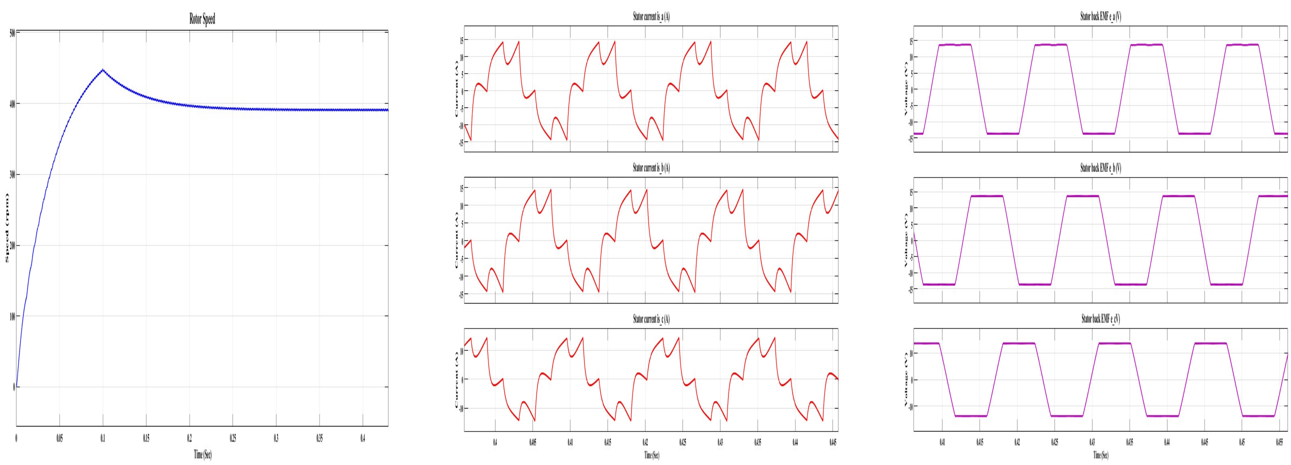


Fig. 7: Close loop simulation diagram of 120°commutation

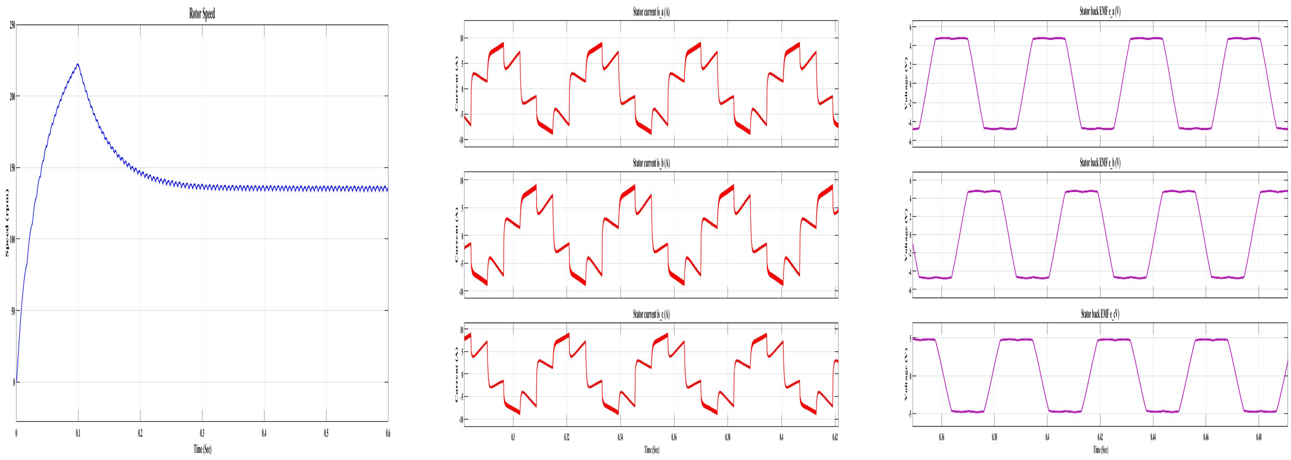
3.2 No PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 8: Waveform of Rotor speed, stator current and back emf when there is no PWM technique applied

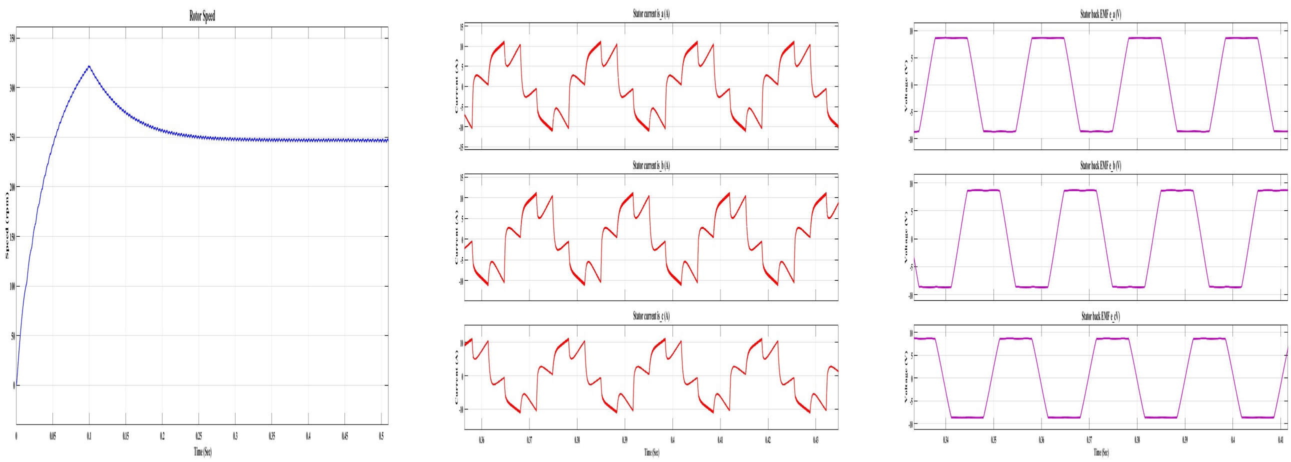
3.3 0.5 PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 9: Waveform of Rotor speed, stator current and back emf when there is PWM technique with duty ratio of 0.5 is applied

3.4 0.7 PWM



(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 10: Waveform of Rotor speed, stator current and back emf when there is PWM technique with duty ratio of 0.7 is applied

3.5 Observation

- We are getting maximum speed as well as very less ripple in speed and current when operating in the No PWM mode. But there is no variation in speed.
- As duty ratio of PWM increase speed of the motor increase.
- With PWM we have more control over range of speeds.

Chapter 3

1 Close loop simulation of BLDC motor

In open loop simulation we will have to manually set duty ratio to get desired speed. So in order to get the desired speed without operating duty ratio manually we need to move to close loop control, where the controller will adjust the duty ratio according to the desired speed.

In this chapter we will discuss the different control technique which can be implemented to speed control of BLDC motor.

1.1 Different close loop control techniques

We are going to discuss following three close loop control technique:

- DC control technique
- Field oriented control technique
- Hysteresis current control technique

1.2 DC control technique

In this control technique, We are controlling the speed of the BLDC Motor by taking the DC side current as reference. So in this control conversion from abc-dq is not required and also number of controller used here is less than the other ac quantity control schemes.

First we will sense the speed and compare it to the reference speed and will generate the error signal. Then the error signal will be given to the controller, the output of the controller will be compare to reference DC side current and output of the comparator will be given to the another controller(Current controller).

Now the output of the current controller will be compare with the triangular signal to generate the required duty ratio.

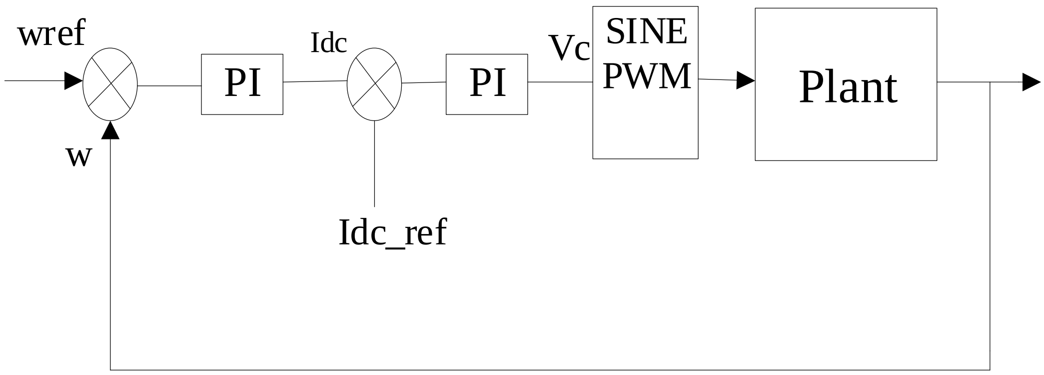


Fig. 1: Block diagram of Dc control technique

1.3 Field oriented control technique (FOC)

In Field Oriented Control, motor currents and voltages are manipulated in the d-q reference frame of the rotor. This means that measured motor currents must be mathematically transformed from the three-phase static reference frame of the stator windings to the two axis rotating d-q reference frame, prior to processing by the PI controllers. Similarly, the voltages to be applied to the motor are transformed from the dq frame of the rotor to the three phase reference frame of the stator before they can be used for PWM output. These transformations generally require the fast math capability of a DSP or high performance processor that are the heart of Field Oriented Control.

Although the reference frame transformations can be performed in a single step, they are best described as a two step process. The motor currents are first translated from the 120 degree physical frame of the motor stator windings to a fixed orthogonal reference frame. They are then translated from the stator fixed frame to the rotating frame of the rotor. Two P-I controllers are used; one for the direct current component, and one for quadrature current. The input to the controller for the direct current and has zero input. This drives the direct current component to zero and therefore forces the current space vector to be exclusively in the quadrature direction.

Since only the quadrature current produces useful torque, this maximizes the torque efficiency of the system. The second P-I controller operates on quadrature current and takes the requested torque as input. This causes the quadrature current to track the requested torque, as desired. The outputs from the two P-I controllers represent a voltage space vector with respect to the rotor. Mirroring the transformation performed on motor currents, these static signals are processed by a series of reference frame transformations to produce voltage control signals for the output bridge. They are first translated from the rotating d-q frame of the rotor to the fixed x-y frame of the stator. The voltage signals are then converted from an orthogonal frame to the 120 degree physical frame of the U, V and W motor windings. This results in three voltage signals appropriate for control of the PWM output modulator.

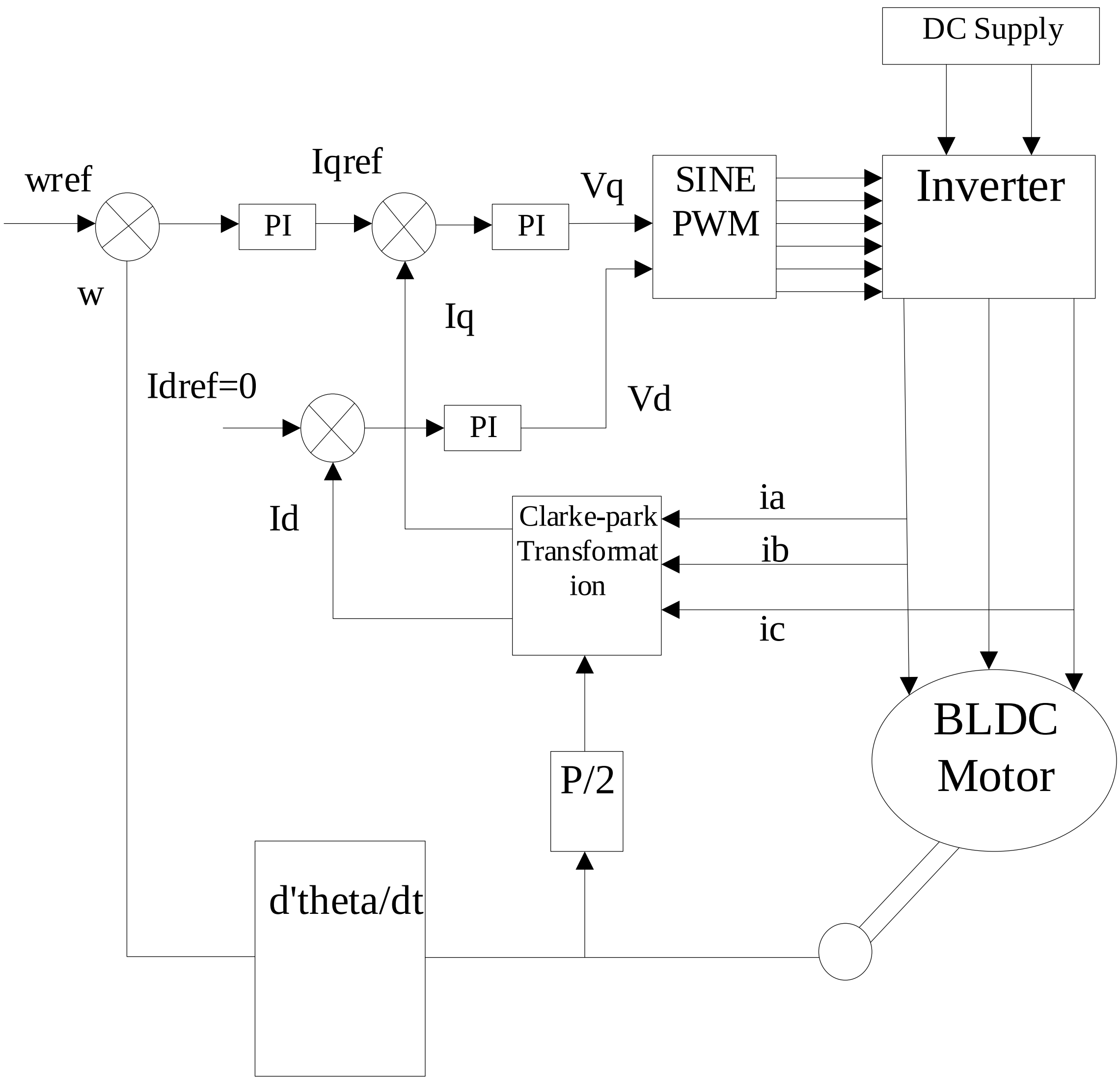


Fig. 2: Block diagram of proposed field oriented control scheme

1.4 Hysteresis current control technique

Hysteresis control is the simplest current control scheme. For closed-loop control of the BLDC motor, two control loops are used. On the outside is the speed control loop, and on the inside is the torque control loop. The Hysteresis bandwidth limits are compared to the current errors to based on control switching action of inverter. Fig. 3. illustrates the Block diagram of the proposed Hysteresis current Control of a BLDC motor.

First Reference speed is compared to the drives' actual speed, and the resulting error is given to speed controller. The controlled signal is compared with the actual torque and error signal is generated. From this error signal actual currents is calculated after dividing by torque constant. This actual current is then compared with the reference current and the error is given to hysteresis block where some finite band for hysteresis control is provided. From the hysteresis block, modulating signal is generated and this modulating signals are then given to sine PWM block to generate the desired switching.

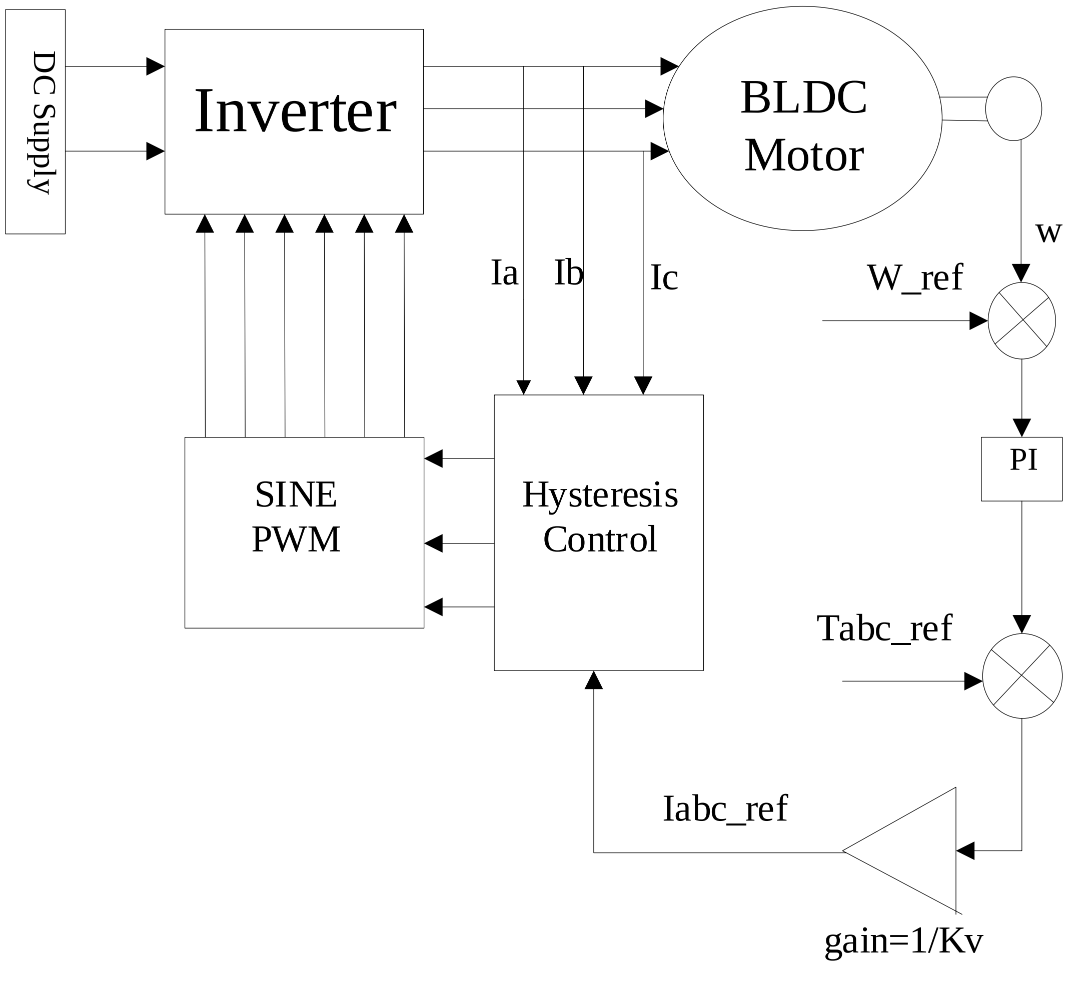


Fig. 3: Block diagram of Hysteresis current control technique

2 120°conduction mode

Here we are using field oriented control (FOC) technique to perform the close loop control of BLDC motor in 120°conduction mode. Here we are going to check whether ripple in speed and stator current is getting reduced or not as compare to open loop simulation.

2.1 Simulation diagram

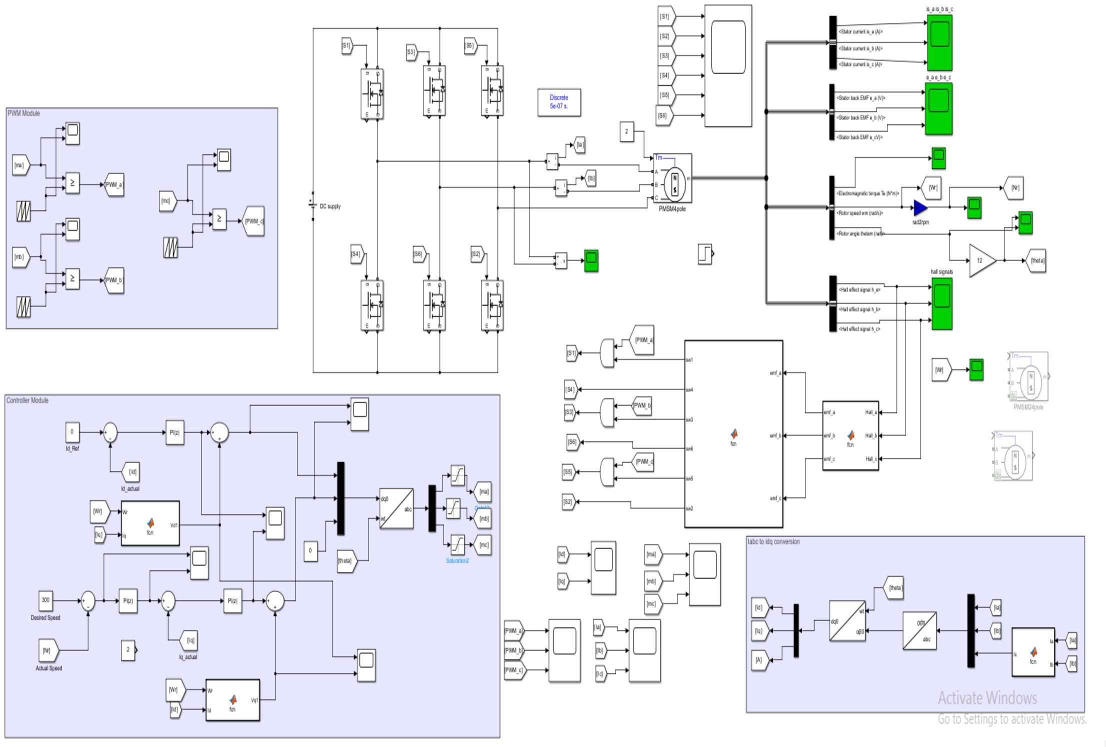
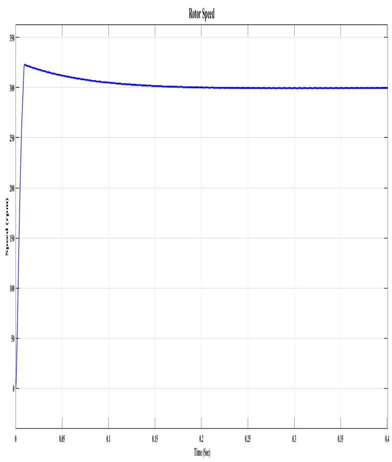


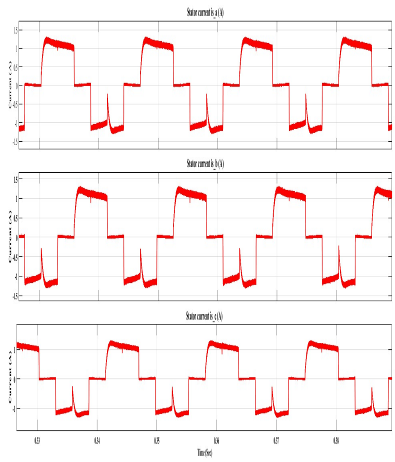
Fig. 4: Close loop simulation diagram of 120°commutation

2.2 Simulation Results

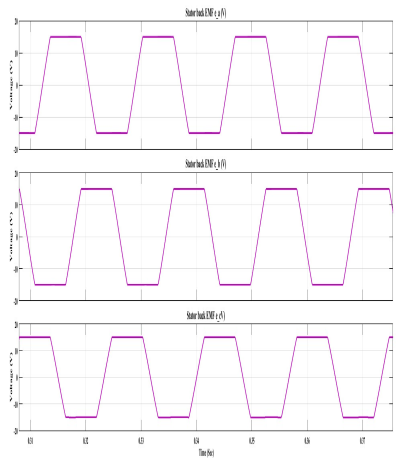
- **For desired speed of 300 rpm**



(a) Rotor Speed

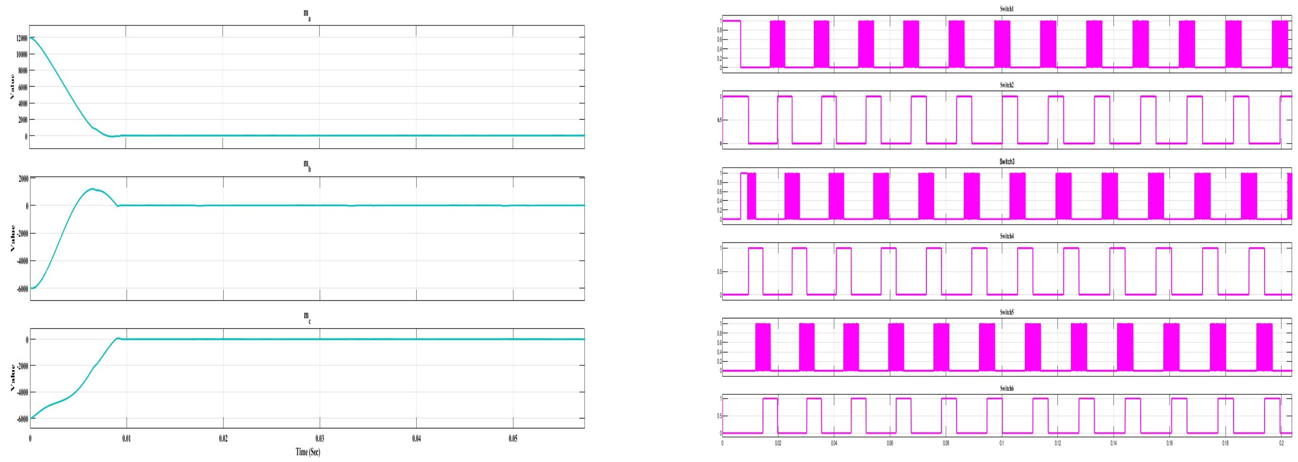


(b) Stator Current



(c) Back emf

Fig. 5: Waveform of Rotor speed, stator current and back emf for desired speed of 300 rpm

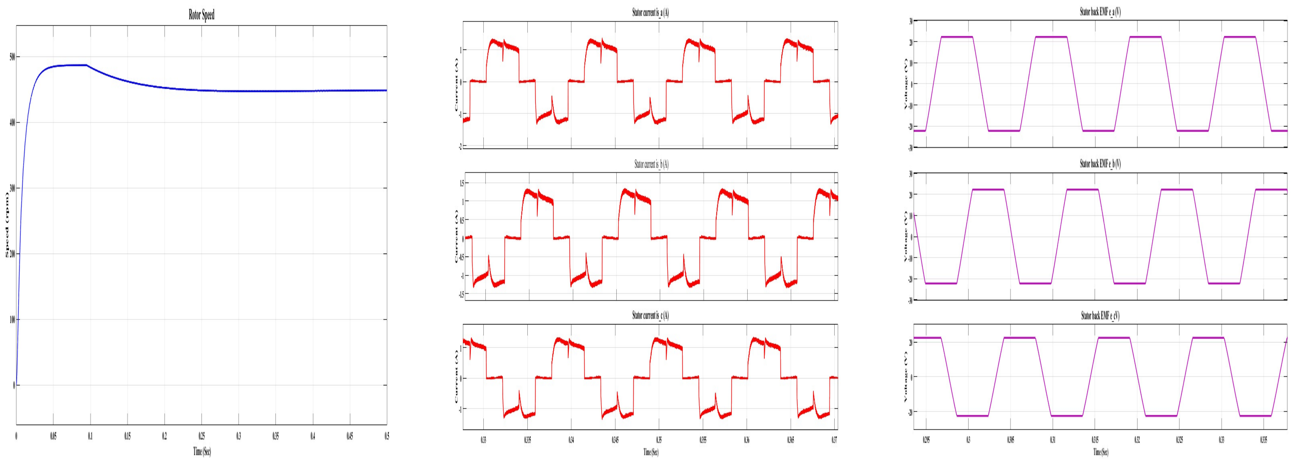


(a) Modulating Signal

(b) Switching pulses

Fig. 6: Waveform of modulating signal and back switching pulses for desired speed of 300 rpm

- **For desired speed of 450 rpm**

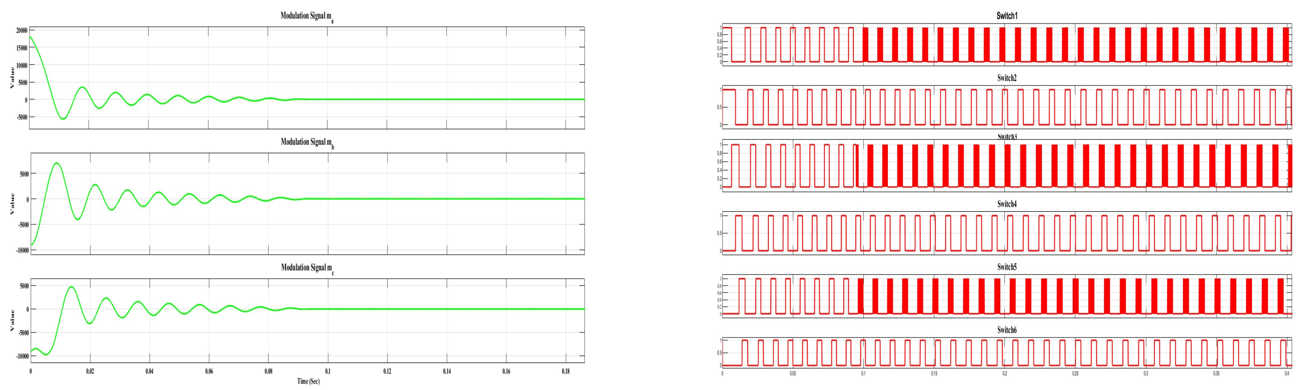


(a) Rotor Speed

(b) Stator Current

(c) Back emf

Fig. 7: Waveform of Rotor speed, stator current and back emf for desired speed of 450 rpm



(a) Modulating Signal

(b) Switching pulses

Fig. 8: Waveform of modulating signal and back switching pulses for desired speed of 450 rpm

2.3 Results

We will vary the all three quantities that is torque, supply voltage and motor speed one by one while keeping other two quantities constant and we will observe the duty ratio in each case.

- **Varying the torque while keeping supply voltage and speed constant**

Tm (N-m)	Supply voltage (V)	Rotor Speed (rpm)	Duty (D)
1 N-m	50 V	300 rpm	0.421
2 N-m	50 V	300 rpm	0.491
3 N-m	50 V	300 rpm	0.547

- **Varying the supply voltage while keeping torque and speed constant**

Supply voltage (V)	Rotor Speed (rpm) A	Tm (N-m)	Duty (D)
50 V	300 rpm	1 N-m	0.614
30 V	300 rpm	1 N-m	–
20 V	300 rpm	1 N-m	–

- **Varying the speed while keeping supply voltage and torque constant**

Rotor Speed (rpm)	Supply voltage (V)	Tm (N-m)	Duty (D)
200 rpm	50 V	1 N-m	0.329
300 rpm	50 V	1 N-m	0.597
450 rpm	50 V	1 N-m	0.866

3 180°conduction mode

Here we are using field oriented control (FOC) technique to perform the close loop control of BLDC motor in 180°conduction mode.

Here we are going to check whether ripple in speed and stator current is getting reduced or not as compare to open loop simulation.

3.1 Simulation diagram

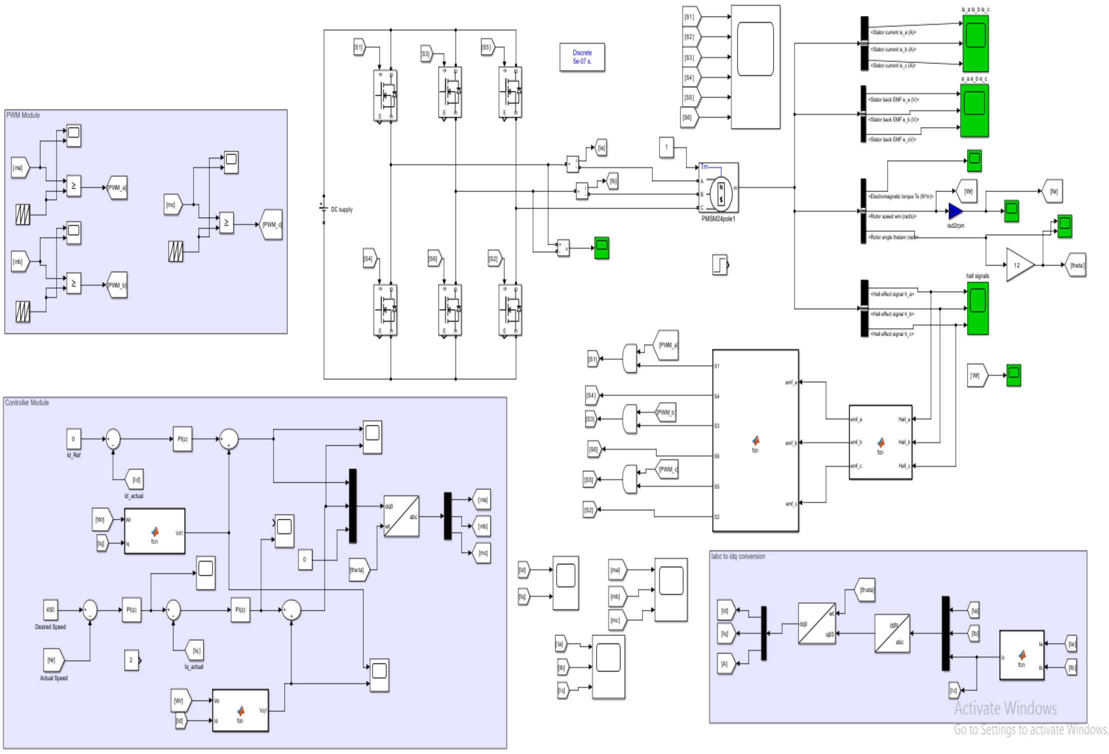
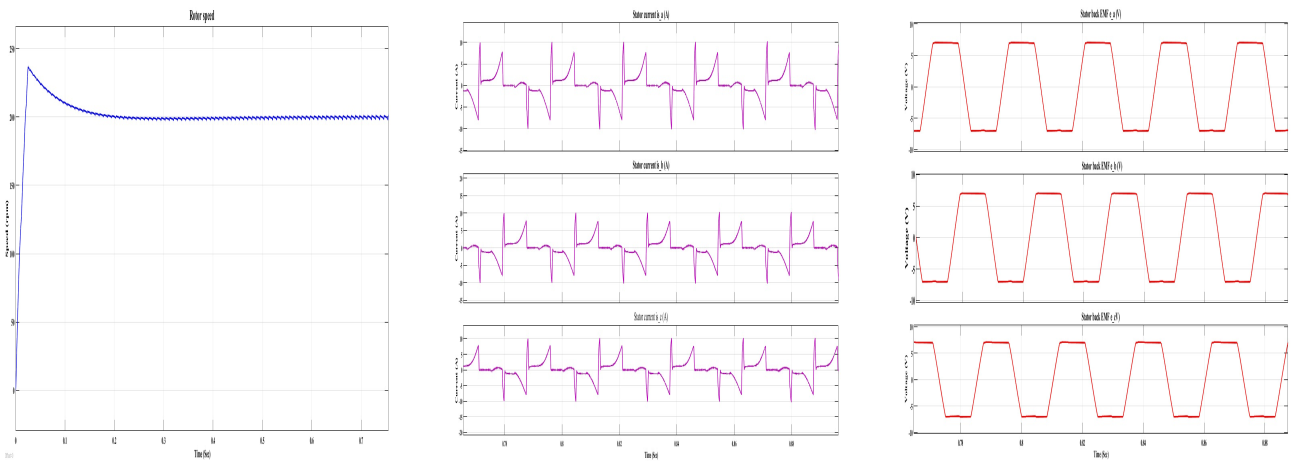


Fig. 9: Close loop simulation diagram of 120°commutation

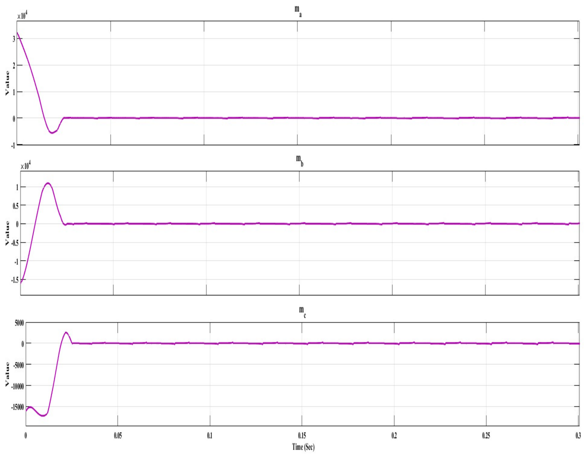
3.2 Simulation Results

- **For desired speed of 200 rpm**

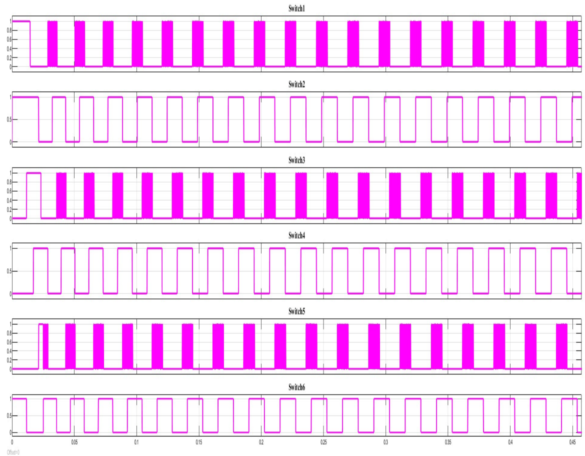


(a) Rotor Speed (b) Stator Current (c) Back emf

Fig. 10: Waveform of Rotor speed, stator current and back emf for desired speed of 200 rpm



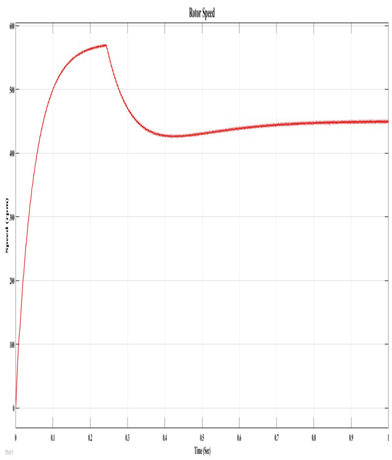
(a) Modulating signals



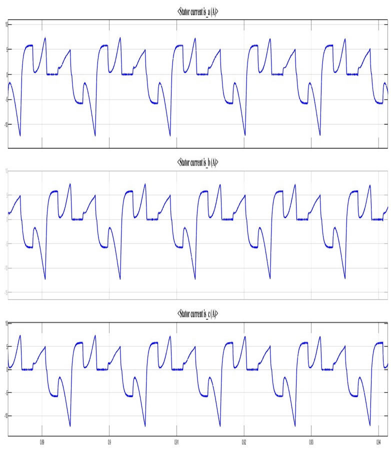
(b) Switching pulses

Fig. 11: Waveform of Modulating signals and back Switching pulse for desired speed of 200 rpm

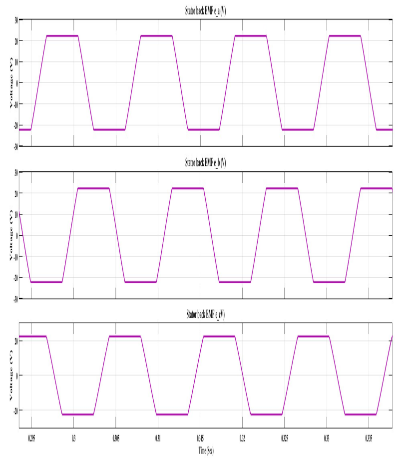
- **For desired speed of 450 rpm**



(a) Rotor Speed

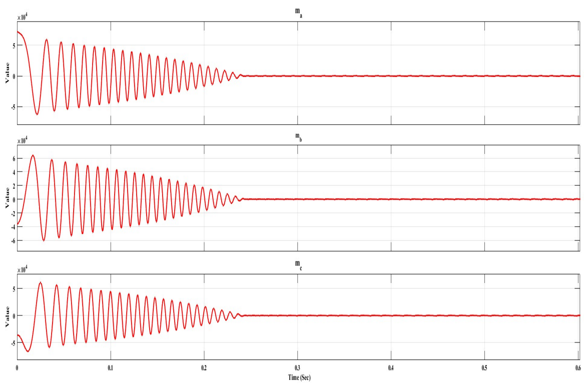


(b) Stator Current

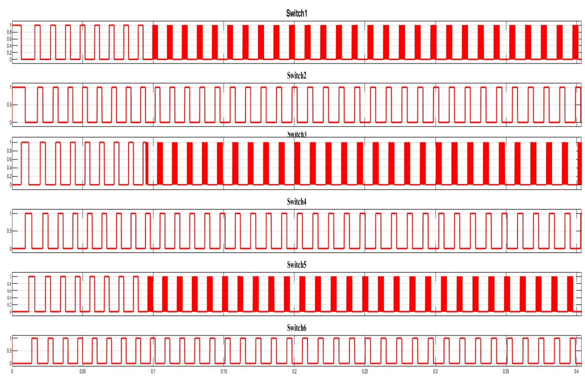


(c) Back emf

Fig. 12: Waveform of Rotor speed, stator current and back emf for desired speed of 450 rpm



(a) Modulating signals



(b) Switching pulse

Fig. 13: Waveform of Modulating signals and back Switching pulse for desired speed of 200 rpm

3.3 Results

- **Varying the torque while keeping supply voltage and speed constant**

Tm (N-m)	Supply voltage (V)	Rotor Speed (rpm)	Duty (D)
1 N-m	50 V	300 rpm	0.50
2 N-m	50 V	300 rpm	0.575
3 N-m	50 V	300 rpm	0.712

- **Varying the supply voltage while keeping torque and speed constant**

Supply voltage (V)	Rotor Speed (rpm) A	Tm (N-m)	Duty (D)
50 V	300 rpm	1 N-m	0.427
30 V	300 rpm	1 N-m	0.564
20 V	300 rpm	1 N-m	–

- **Varying the speed while keeping supply voltage and torque constant**

Rotor Speed (rpm)	Supply voltage (V)	Tm (N-m)	Duty (D)
200 rpm	50 V	1 N-m	0.331
300 rpm	50 V	1 N-m	0.432
500 rpm	50 V	1 N-m	0.745

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