Advanced Power Conversion System for Six-Switch and Four-Switch Brushless Permanent Magnet Motor Drives in Electrified Vehicles

by

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Abstract

This thesis presents a power conversion system for six-switch BLDC motor drive and four-switch BLDC motor drive. Brushless DC (BLDC) motor drive have the advantage of high efficiency, high power density and low maintenance. These advantages make BLDC motor drive be widely used in industrial applications. In addition, the four-switch inverter will reduce the cost of the system with less switches. However, the problem of torque pulsation of four- switch BLDC motor drive is an intrinsic problem. To reduce torque pulsation, a novel DC/DC converter whose name is multi-purpose bi-directional DC/DC converter will be proposed in the thesis. This DC/DC converter with diode-assisted network will help improve boost ratio for the input of the BLDC motor drive. For the control system, PI controllers are used to control DC/DC converter and hysteresis control is employed for BLDC motor drive. Though there are other advanced methods for control, the PI controllers and hysteresis control can reduce the complexity of the whole system. Both six-switch and four-switch BLDC motor drives with the proposed system are simulated in PSIM software and the results are compared and discussed.

Chapter 1 Introduction

1.1 Background

In the past few decades, the field of power electronics has experienced significant progress and extensive research. The technology of power electronics emphasizes improving the efficiency, performance, reliability, robustness, cost-effectiveness and life of the system. Brushless DC (BLDC) motor drive is widely used due to its simple structure, high reliability, high efficiency, better speed and torque characteristics, noiseless operation, and high power density. Until now, researchers tried many methods to reduce cost of the system, one of that was to apply four-switch inverter. Compared to traditional six-switch inverter, the four-switch inverter decreases one switch leg. Though four-switch inverter could reduce cost of the system, the problem of torque pulsation raises, which is an intrinsic problem.

To reduce the cost of the system, researchers always pursue the structural improvements while improve the performance of the system, increase efficiency and decrease motor torque ripple. To decrease the torque pulsation, the proposed system employs a new scheme, which include "multi-purpose bi-directional DC/DC converter" and "diode-assisted network". The multi-purpose bi-directional DC/DC converter contains an energy storage, which will charge/discharge. With this structure, the proposed system could be used in solar power system and wind power system. The diode-assisted network is a X-shaped diode-capacitor network. By charging and discharging the capacitors, the network will provide a high voltage multiplication factor. Compared to conventional boost DC/DC converter, the gain of this scheme is higher, but more elements would be used.

For the DC/DC converter, it should help solve the problems like output voltage fluctuating and output power fluctuating. The DC/DC converter should demonstrate high operating efficiency, high boost gain and small current ripple. Regard to the development of DC/DC converter topology,

researchers make a lot of efforts. A dual-switch boost DC/DC converter was proposed in [1]. This converter contains two switches and two inductors. The switches will be turned on or off at the same time. Thus, the control of this converter will be relatively simple. This converter also has the advantages of less devices, small circuit size, and low cost [2]. Considering the dual-switch boost DC/DC converter and the multi-purpose bi-directional DC/DC converter with diode-assisted network, later one can generate higher boost ratio, due to the addition of the energy storage. Therefore, the multi-purpose bi-directional DC/DC converter and diode-assisted network would be implemented in the proposed system.

For the control of the proposed system, space vector control is a relatively new but complicated method. A current control algorithm for torque ripple reduction of four-switch BLDC motor was proposed in [3]. The main idea of this algorithm was setting several vector bases according switches modes of the inverter and then using this vector bases to generate desired voltage vectors and reach the requirements of control. The disadvantage of this method is that the vector bases do not contain null vector. Taking into account that the multi-purpose bi-directional DC/DC converter also includes switches, the synchronous control for DC/DC converter and BLDC motor drive will be complicated. PI controllers and hysteresis control would be used in the control of the proposed system and the control of the DC/DC converter and BLDC motor drive would be separated.

Actually, PMAC motors are widely used in the applications of electric vehicles, due to its low ripple. However, for the light electric vehicles, BLDC motors, due to its simple control and low cost, are used and help contribute to the improvement of a vehicle's power economy. Thus, the whole proposed system is designed for light electrified vehicle, such as scooter and small motorcycle [4][5].

A simulation model will be designed and developed to analyze performances of the proposed converter and motor drive structures and the results will be presented in detail. The comparation of the proposed power conversion system between six-switch BLDC motor drive and four-switch BLDC motor drive will be presented.

1.2 Thesis Outline

Chapter 2 introduces four-switch and six-switch BLDC motor drives and conducts a study on the multi-purpose bi-directional DC/DC converter and the diode-assisted network. Comparison between conventional approaches and advanced scheme will be presented.

Chapter 3 describes the proposed structure and introduces the control system.

Simulation results for proposed power conversion system will be presented in Chapter 4. It also includes discussion of performance between four-switch and six-switch BLDC motor drives. Chapter 5 will conclude the research mention the future work of this research.

Chapter 2 Literature Study and Conventional Approach

2.1 Six-Switch and Four-Switch BLDC Motor Drives

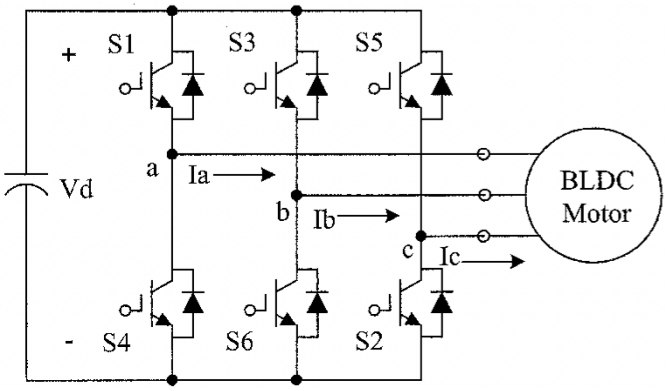


Fig. 2.1 Six-switch BLDC motor drive system [6]

Fig. 2.1 shows the conventional six-switch BLDC motor drive system. Three phases of the motor drive are typically attached to the six-switch inverter, with one phase connecting to one switch. The BLDC motor can be represented by three phase stator windings which have a resistive element, an inductive element and a back EMF voltage drop. According to the schematic figure of the six-switch BLDC motor drive, the switching sequences and working modes can be gained, as shown in Fig. 2.2

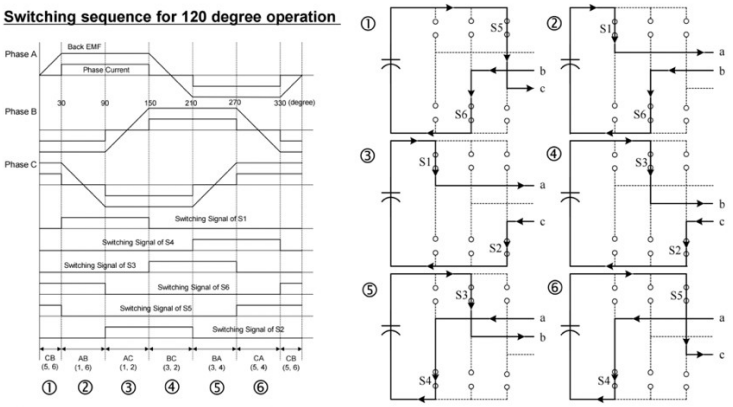


Fig. 2.2 Switching sequences for six-switch BLDC motor drive

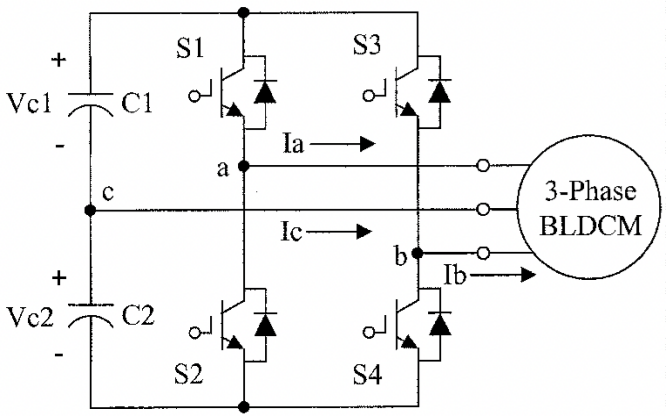


Fig. 2.3 Four-switch BLDC motor drive system [6]

Fig. 2.3 shows the four-switch BLDC motor drive system. Different from the six-switch BLDC motor drive, one phase of the four-switch BLDC motor connects to the midpoint of DC-Bus capacitors. Thus, this phase current is flowing and cannot be controlled directly.

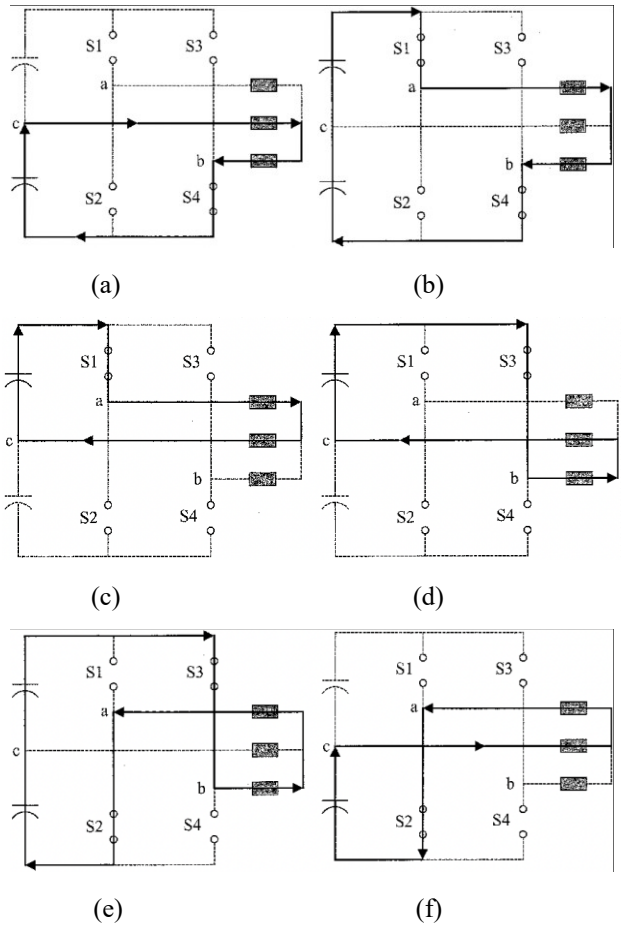


Fig. 2.4 Switching sequences for four-switch BLDC motor drive [6]

Table 2.1 Switching sequences for four-switch BLDC motor drive

Modes	Active Phase	Switching Devices
Mode I	+C, -B	S_4
Mode II	+A, -B	S_1, S_4
Mode III	+A, -C	S_1
Mode IV	+B, -C	S_3
Mode V	+B. -A	S_2, S_3
Mode VI	+C, -A	S_2

As shown in Fig. 2.4 and Table 2.1, the four-switch BLDC motor drive also have six modes which can satisfy the work of three phases in BLDC motor drive. In mode III, the current flows between phase A and phase C, and I_b is zero. Mode III can be divided in two sub-modes, as shown in Fig. 2.5. In this mode, switch S_1 is turned on for supplying DC-link voltage to increase current. As shown in Fig. 2.5(a), when S_1 is turned on, I_a increase and $I_c = -(I_a + I_b) = -I_a$ ($I_b = 0$). When I_a reaches the upper limit, S_1 is turned off and the current flows through D_2 (diode of S_2), as shown in Fig.2.5(b). Thus, I_a will decrease. Mode I, IV and VI work in the same way. On the other hand, in mode II, the motor drive work in the same principle. Switches S_1 and S_4 are turned on to increase the current; when S_1 and S_4 are turned off, the current will flow through D_2 and D_3 to decrease the current. Mode V works in the same way. Thus, in six modes, half of DC-link voltage is supplied to BLDC motor drive in four modes, and full DC-link voltage is supplied in other two modes.

Compared to six-switch BLDC motor drive, the difference of voltage supply in four-switch one brings some problems. One is that when half of the DC-link voltage is supplied, the current cannot increase as much as full DC-link voltage. It may result in distortion of current waveform and torque ripple. The other is the speed limitation, since the operating speed of the BLDC motor is determined by the back EMF and DC-link voltage. The supply of half of the DC-link voltage will cause the decrease of the operating speed.

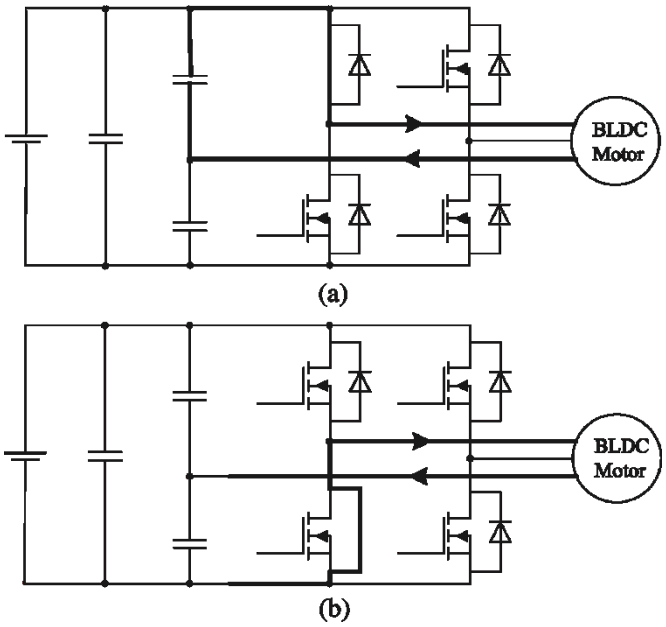


Fig. 2.5 Sub-modes of mode III (a) Sub-mode III-1 (b) Sub-mode III-2

2.2 Multi-Purpose Bi-Directional DC/DC Converter

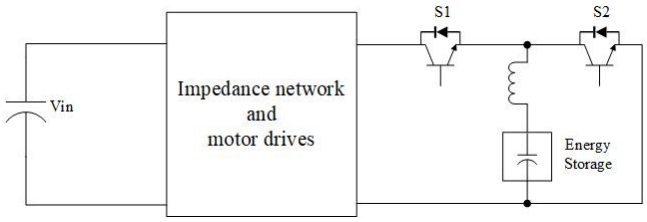


Fig. 2.6 System diagram

The multi-purpose bi-directional DC/DC converter can boost DC-link voltage and charge/discharge energy storage. The system diagram is shown in Fig. 2.6. For a charging mode, the switch S_1 is turned on for a longer time than switch S_2; for a discharging mode, switch S_2 is turned on for a longer time. The switching strategy is shown in Fig. 2.7.

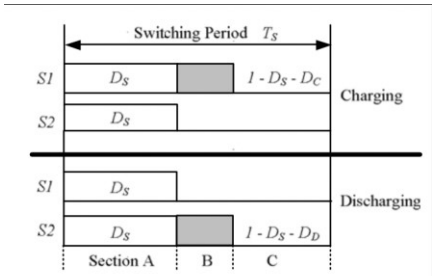


Fig. 2.7 Switching strategy for charging and discharging modes [7]

In Fig. 2.7, T_s is a switching period; in duty ratio D_s , switch S_1 and S_2 are turned on; in duty ratio D_c (additional switch S_1 ON period), the energy storage is charged; in duty ratio D_s (addition switch S_2 ON period), the energy storage is discharged. By charging and discharging the energy storage, the current can flow bi-directionally.

2.3 Diode-Assisted Network

The conventional Ćuk converter is shown in Fig. 2.8.

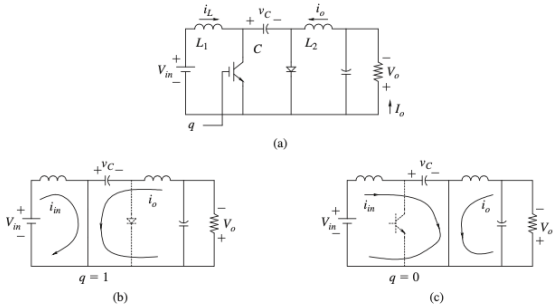


Fig. 2.8 Ćuk converter [8]

Fig. 2.8 (b) and (c) show the cases of switch q ON and OFF. In steady state, equating the net change in charge on the capacitor over switching period to zero, the gain of voltage can be shown a

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \tag{2.1}$$

where D refers to the conductive duty ratio of switch q. Though the gain of conventional DC/DC converter can reach to infinity theoretically, in practical cases the maximum gain would be limited due to the non-ideal conditions. To make the gain as large as possible, the switch q should be turned on as long as possible. Since the switching frequency is large, it would force the switch to be turned ON and OFF in a short time duration. The addition of diode-assisted network will avoid using the large D as well as produce a large gain.

Fig. 2.9 shows the Ćuk-derived buck-boost converter with the diode-assisted capacitor network. When the switch SW is turned on, the inductive current i_L flows from DC source to charge the inductor L. Diode D_1 and D_2 are inverse-biased, so they can be regarded as open circuit.

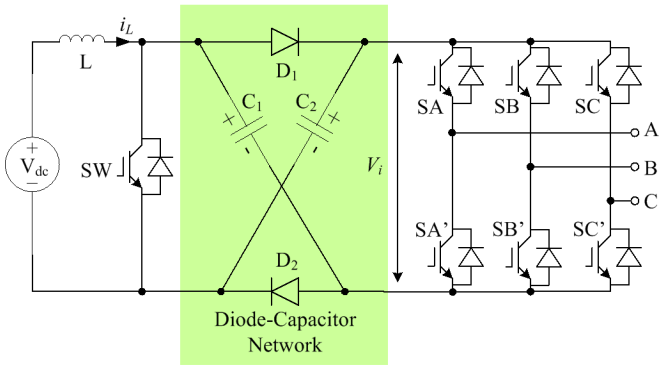


Fig. 2. 9 Ćuk-derived buck-boost converter with a diode-assisted network [9]

Thus, capacitors C_1 and C_2 are in series with switch SW connecting the positive pole of C_1 with negative pole of C_2, as shown in Fig. 2.10 (a). The DC-link voltage $V_i = V_{c_2} - \left(-V_{C_1}\right) = 2V_c$ (assume $C_1 = C_2 = C$). When the switch SW is turned off, the inductive current i_L flows through the diode-assisted network. Diode D_1 and D_2 are forward-biased to connect capacitors C_1 and C_2 in parallel, as shown in Fig. 2.10 (b). Two capacitors are charged.

The minimal commutation count criteria is studied in [10]. It makes gain of the converter with diode-assisted network to be written as

$$\frac{\hat{v}}{V_{dc}} = \frac{1+D}{1-D} \tag{2.2}$$

where $\hat{v}$ represents the peak AC output voltage. Comparing (1) and (2), the implementation of diode-assisted network is effective.

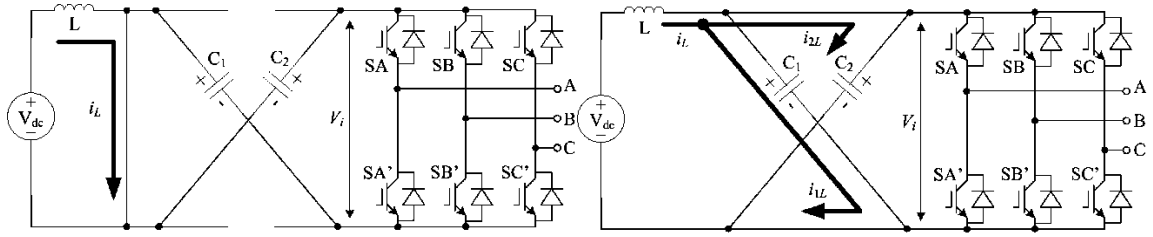


Fig. 2. 10 Equivalent circuit of Ćuk-derived DC/DC converter with diode-assisted network [9] (a) ON (b) OFF

2.4 BLDC Motors

BLDC motor is a synchronous machine with a permanent magnet rotor. Unlike DC motors, which use commutator and brushes in mechanical way, BLDC motors complete polarity reversal with switches electronically. This reduce maintenance cost for BLDC motors [11].

According to how the permanent magnets are mounted on the rotor, the BLDC motors can be classified into two kinds, which are shown below:

1) Surface-Mounted Permanent Magnet Motor

This kind of motors is easy to build because the permanent magnets are mounted on the circle surface of the rotor. However, this building way make the motor be at the risk of the connected permanent magnets flying apart when it is running at a high speed. The structure of this motor helps to minimize cogging torque. For this motor, the inductance variation caused by rotor position is small and can be ignored, generally. The structure of this surface-mounted rotor is shown in Fig. 2.11 [11].

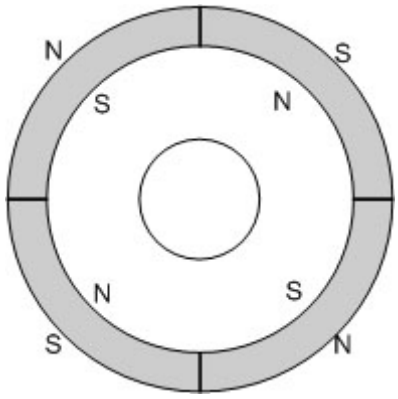


Fig. 2.11 Surface-mounted PM rotor [11]

2) Interior-Mounted Permanent Magnet Motor

Unlike surface-mounted PM motors, permanent magnets of this kind are mounted inside the rotor, as shown in Fig. 2.12.

This interior-mounted permanent magnet rotor is an ideal choice to work at high speed. However, since the air gap varies with the rotor position, the change of inductance cannot be ignored [11].

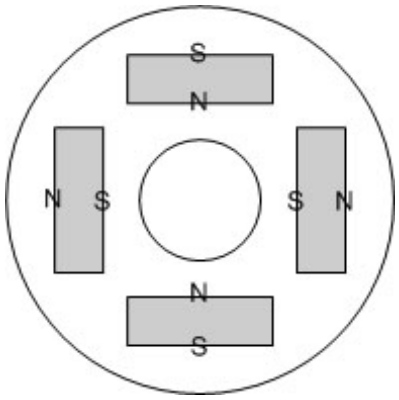


Fig. 2.12 Interior-mounted PM rotor [11]

According to the shape of back-EMF, the permanent magnet motors also can be classified into trapezoidal shape back-EMF type and sinusoidal shape back-EMF type, which are described as follow:

1) Trapezoidal Shape Back-EMF Type

In this kind of motors, a constant torque can be generated by the trapezoidal shape back-EMF and square shape current. For this trapezoidal shape back-EMF motor, the requirement of resolution for rotor position sensor is much lower such as hall sensor since it needs only six commutation instants for each electrical cycle. The structure of this type of BLDC motor is shown in Fig. 2.13 [11].

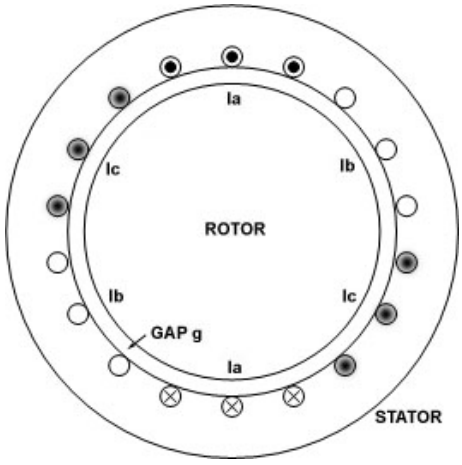


Fig. 2.13 Structure of the trapezoidal back-EMF type of BLDC motor [11]

2) Sinusoidal Shape Back-EMF Type

For this type of motor, the generated back-EMF should be a sinusoidal wave function of rotor angle. It has a sinusoidal winding distribution, which is shown in Fig. 2.14. This type of motor is regarded as a PMSM (permanent magnet synchronous machine) rather than a BLDC [11].

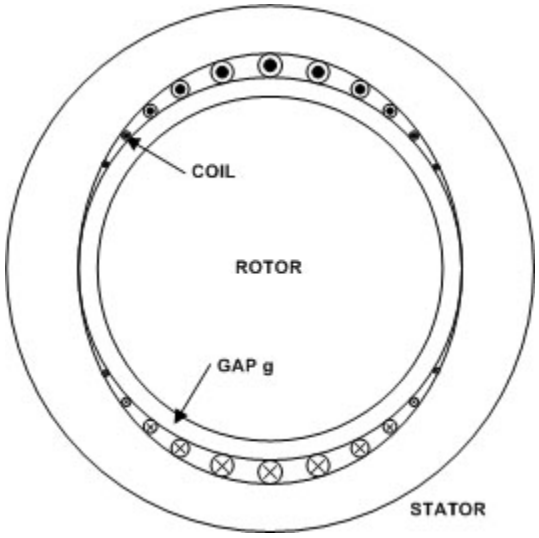


Fig. 2.14 Structure of sinusoidal back-EMF type of motor [11]

Chapter 3 Proposed Structure and Control

3.1 Proposed Six-Switch BLDC System

Based on the study and methods mentioned in Chapter 2, the proposed system combines these structures and makes them work in a proper way. The system diagram for six-switch BLDC motor drive is shown in Fig. 3.1.

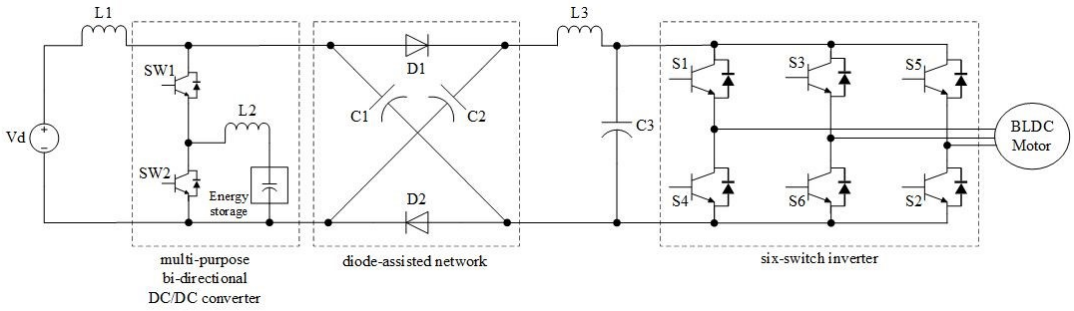
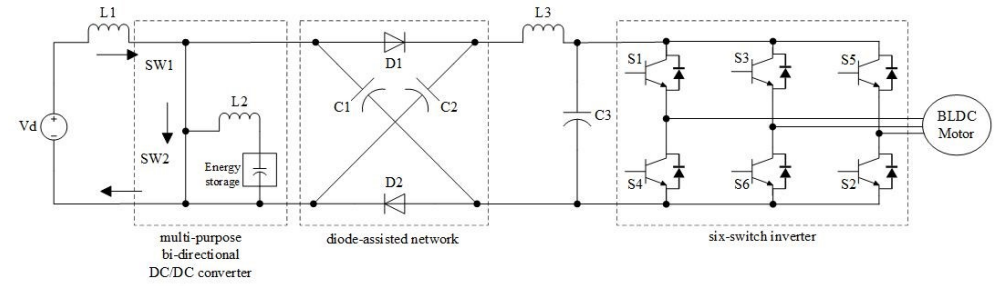


Fig. 3.1 System diagram for proposed system with six-switch BLDC motor drive

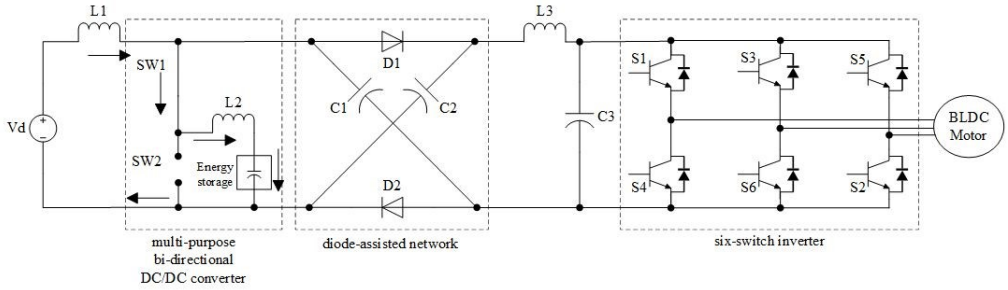
As shown in Fig. 3.1, the multi-purpose bidirectional DC/DC converter is in the front part of the proposed system, and the diode-assisted network interfaces between the DC/DC converter and the six-switch inverter. There are totally four operation modes for two switches (SW_1 and SW_2) of multi-purpose bi-directional DC/DC converter. The equivalent circuits for these four modes are shown in Fig. 3.2. The switching strategy for charging and discharging modes are same as the situation in Fig. 2.7.

As shown in Fig. 3.2 (a), in both charging and discharging modes, SW_1 and SW_2 could be in this state. In this case, in the diode-assisted network, the diodes are reverse biased, and the input of the inverter equals to two times of the voltage of C_1 ($C_1 = C_2$). SW_1 and SW_2 could be in the state which is shown in Fig. 3.2 (c) in both charging and discharging modes. In this case, the diodes in the diode-assisted network are forward biased, and the input of the inverter equals to the voltage of C_1. The difference between charging and discharging modes is that SW_1 will be turned on for

an additional time in charging mode (as shown in Fig. 3.2 (b)) and SW_2 will be turned on for an additional time in discharging mode (as shown in Fig. 3.2 (d))



(a)



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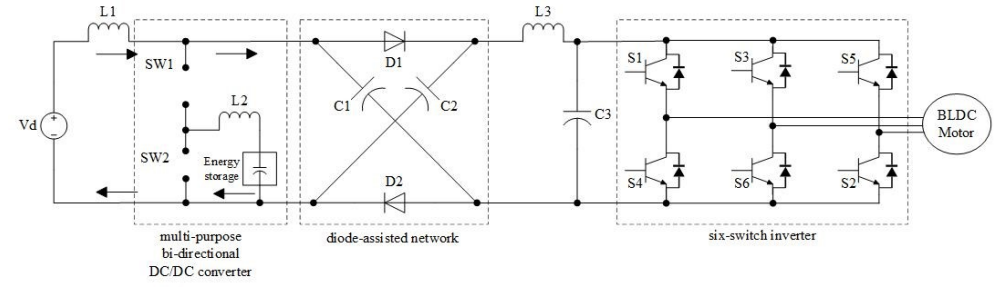
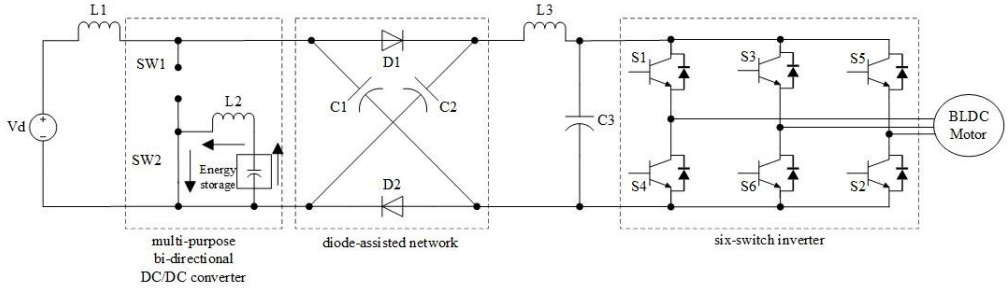


(c)



(d)

Fig. 3.2 The equivalent circuits for four modes of switches in DC/DC converter
(a) SW_1 and SW_2 on (b) SW_1 on, SW_2 off (c) SW_1 and SW_2 off (d) SW_1 off, SW_2 on

The charging of the energy storage would not have impact on the power conversion to the inverter. Moreover, the discharging of the energy storage would supply larger voltage for the diode assisted network to boost and the input voltage of the inverter would be larger.

3.2 Proposed Four-Switch BLDC Motor

The structure of the proposed power conversion system for four-switch BLDC motor drive is the same as six-switch one, in general. The difference is that the capacitor in front of the inverter would be separated to two capacitors and one arm of the BLDC motor drive connects to the midpoint of these two capacitors. The system diagram for four-switch BLDC motor drive is shown in Fig. 3.3.

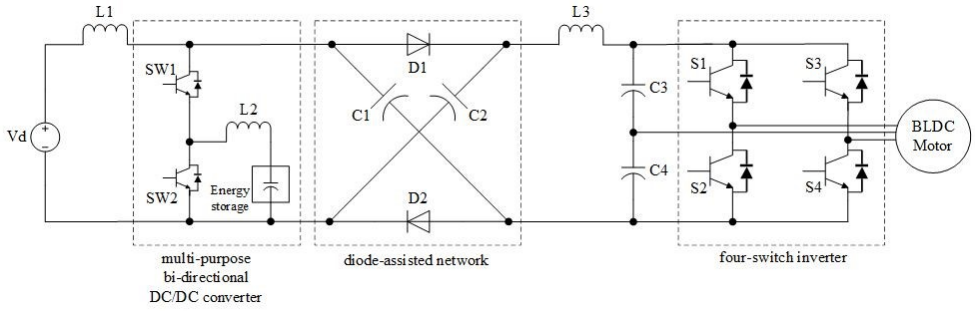


Fig. 3.3 System diagram for proposed system with four-switch BLDC motor drive

The working modes of the multi-purpose bi-directional DC/DC converter and diode-assisted network for four-switch BLDC motor drive are the same as six-switch one.

3.3 Control Network

For the proposed power conversion system, two separated control systems would be utilized for switches in the multi-purpose bi-directional DC/DC converter and BLDC motor drive. PI controllers would be used for switches in the DC/DC converter and hysteresis controllers would be used for BLDC motor drive.

3.3.1 The Control System for Switches in DC/DC Converter

The PI controller stands for proportional and integral. The transfer function of PI controller can be written as

$$G(s) = K_P + K_I \frac{1}{s} \tag{3.1}$$

$$= K_P \left(1 + \frac{1}{sT}\right) \tag{3.2}$$

where K_P is proportional gain, K_I is integral gain and T is time constant. The proportional term provides overall control with proportional to the error signal through a full gain factor and the integral term reduces steady-state errors through low-frequency compensation of the integrator. PI controller is based on feedback, and K_P is proportional gain which indicates the magnification of the difference between the reference value and feedback value. If the proportional gain is too high, the change of the controlled value might be large and then result in unstable system. The integral accumulate error between the reference value and the feedback value. When the difference integral is accumulated to a certain value, it would reprocess to avoid oscillation. The integral term might cause controlled value to overshoot. The output of the PI controller can be written as

$$U(t) = K_P e(t) + K_I \int_0^t e(t)\, d(t) \tag{3.3}$$

The input voltage of the inverter is used as benchmark to control switches in the DC/DC converter (SW_1 and SW_2). With the control system, the input voltage of the inverter could maintain in the required value. The switching actions also are determined by the current of the energy storage. This part indicates the additional charging or discharging time of the DC/DC converter. To maintain the required value of the current of energy storage, SW_1 and SW_2 need to be turned on or off to charge or discharge the energy storage. This control system would implement PI controllers. The diagram of this control system is shown in Fig. 3.4.

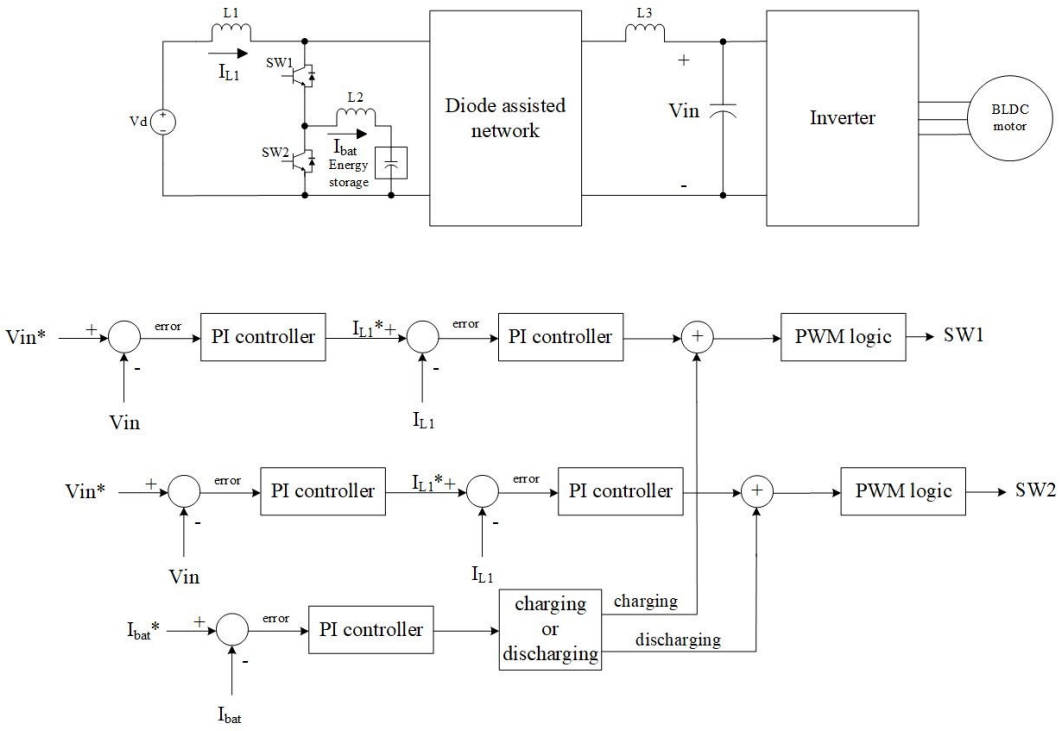


Fig. 3.4 Diagram of the control system for switches in DC/DC converter

3.3.2 The Control System for BLDC Motor Drive

To control the BLDC motor drive, the control system works on turning on and off the switches in the inverter. To make the control work in a fast respond speed, the control of the current of the BLDC motor drive would implement hysteresis control. Hysteresis control is a feedback controller that quickly changes between two states. In four-switch inverter case, the feedback regulation of PI controller is slower than hysteresis control which would cause the current waveform to be unsatisfactory. Moreover, if the four-switch BLDC motor drive implement PI controllers, the complexity of control would increase since phase *a* current and phase *b* current should be controlled separately. Thus, to make a comparison between six-switch BLDC motor drive and four-switch one, these two kinds of BLDC motor drives would use hysteresis control. The schematic diagram of hysteresis control is shown in Fig. 3.5.

As shown in Fig. 3.5, there is a bandwidth limitation in hysteresis control, and the change of current would be controlled in this bandwidth. When the current exceeds the upper limit, the

switch will be turned off and the current will be forced to decrease; when the current reduces below the lower limit, the switch will be turned on and the current will increase.

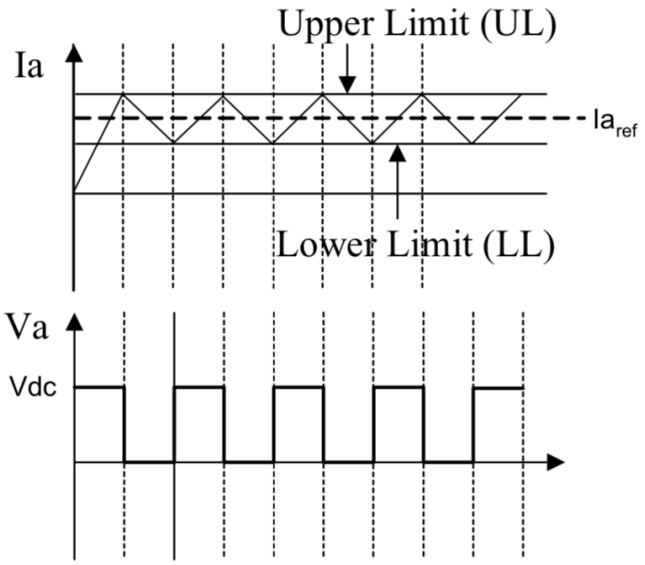


Fig. 3.5 Schematic diagram of hysteresis control

In the BLDC motor drive, the output of hall sensor of each phase is associated with the corresponding phase current. Thus, in the control system, setting a current reference and multiplying it by each output of hall sensor can set current reference for each phase current. In this case, the phase currents can be controlled separately.

Chapter 4 Simulation Study and Discussion

In this chapter, several models are built and simulated in PSIM software. The BLDC motor and load parameters implemented in these models are the same. The setting parameters of the BLDC motor are: stator resistance $R = 11.9\Omega$, stator self-inductance $L = 0.00207H$, stator mutual inductance $M = -0.00069H$, number of poles $P = 4$, moment of inertia $J = 4\times10^{-5}$ kg·m·m. The setting parameters of the load are: $T_c = 0$, $K_1 = 0.02$, $K_2 = 0$, $K_3 = 0$. According to the load torque calculation formula provided in PSIM software:

$$T_{load} = sign(\omega_m)(T_c + K_1|\omega_m| + K_2|\omega_m|^2 + K_2|\omega_m|^3) \quad (4.1)$$

where $sign(\omega_m)$ is the sign function based on ω_m (motor speed). When motor speed is greater than zero, $sign(\omega_m) = 1$; when motor speed is lower than zero, $sign(\omega_m) = -1$.

4.1 Results for Conventional Six-Switch BLDC Motor Drive

Conventional six-switch BLDC motor drive was developed and simulated in PSIM software. The developed model is shown in Fig. 4.1 and the control of BLDC motor drives is based on hysteresis control, which is same as the control of BLDC motor drive in six-switch and four-switch case with proposed system. The DC source voltage is 400V and the reference of phase current is 6A.

Model was simulated to obtain results which are shown in Fig. 4.2. Fig. 4.2 (a) shows three phase currents of BLDC motor drive. Fig. 4.2 (b) shows motor speed. Fig. 4.2 (c) shows motor torque.

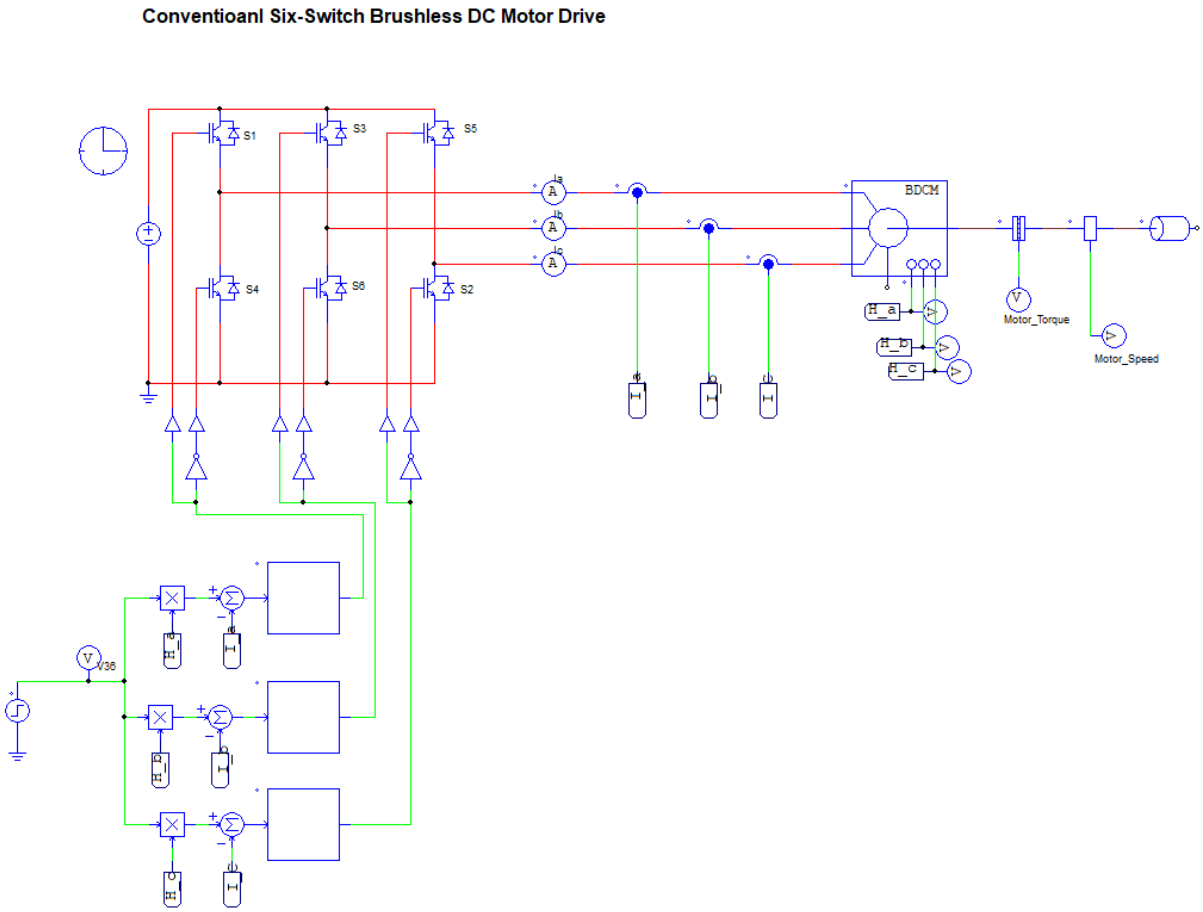
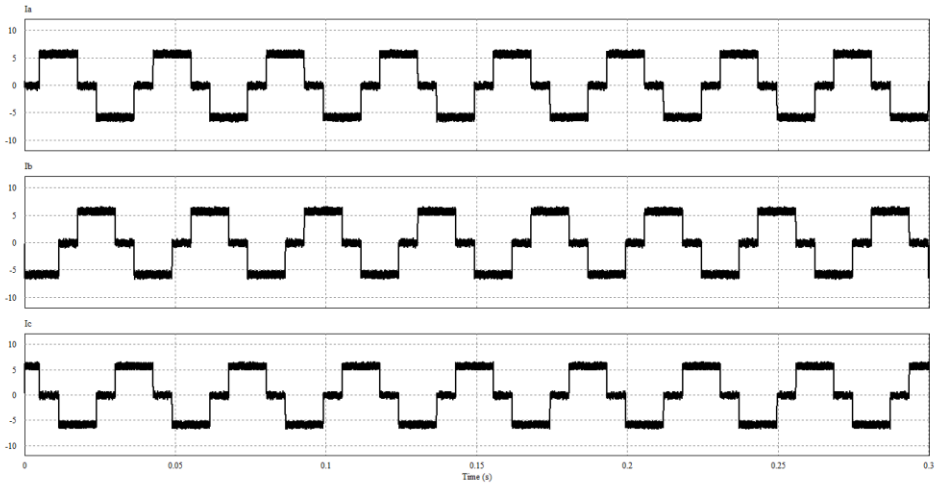
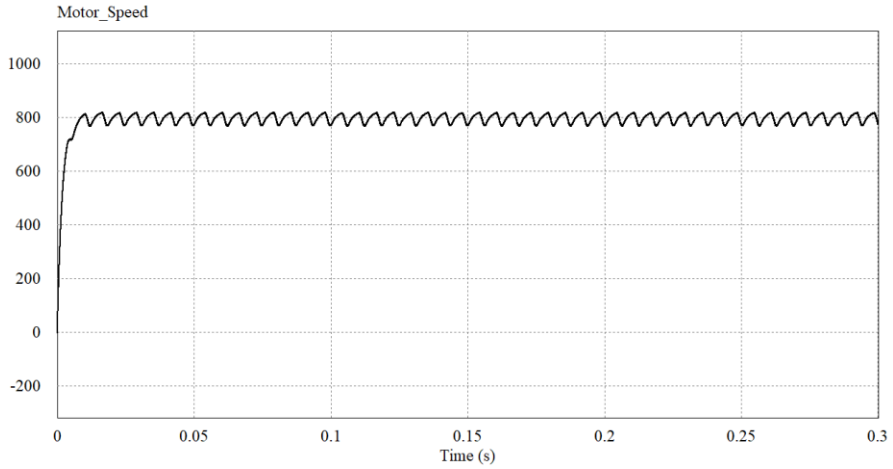


Fig. 4.1 Conventional six-switch BLDC motor drive model

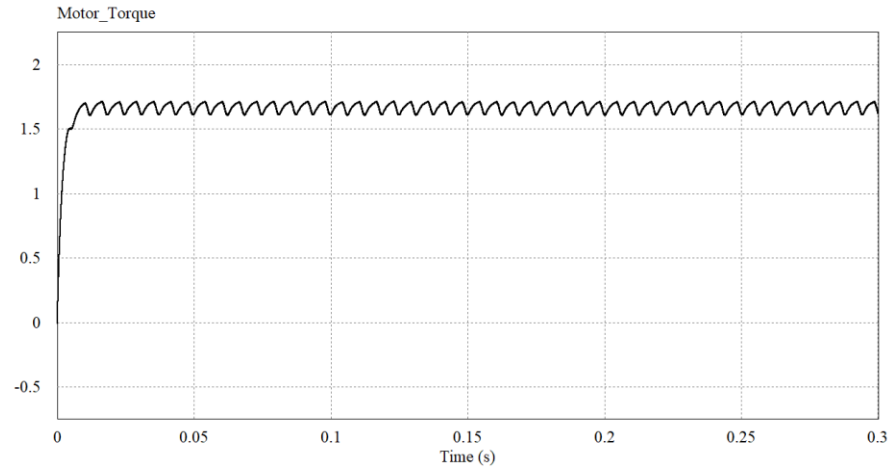
As shown in Fig. 4.2 (a), the amplitude of phase current stabilized at 5.5A and the waveform of phase current has ripple. According to Fig. 4.2 (b), the motor speed can be controlled at 800rpm. The motor torque is 1.662N·m approximately in steady state. From (4.1), the torque $T_{load} = sign(\omega_m)(0.02|\omega_m|) = 0.02 \times 800 \times \frac{2\pi}{60} = 1.675\text{N·m}$. The simulation result of torque approximately equals to the theoretical value. The waveforms of motor speed and motor torque have ripple as well.



(a)



(b)



(c)

Fig. 4.2 Simulation results for conventional six-switch BLDC motor drive (a) Three phase currents (b) Motor speed (c) Motor torque

4.2 Results for Conventional Four-Switch BLDC Motor Drive

The model of conventional four-switch BLDC motor drive was developed and simulated as shown in Fig. 4.3. In this model, the control of motor speed is based on hysteresis control, which is also same as the control of BLDC motor drive in six-switch and four-switch case with proposed system. The sources DC voltage are 200V separately and the reference phase current is 6A.

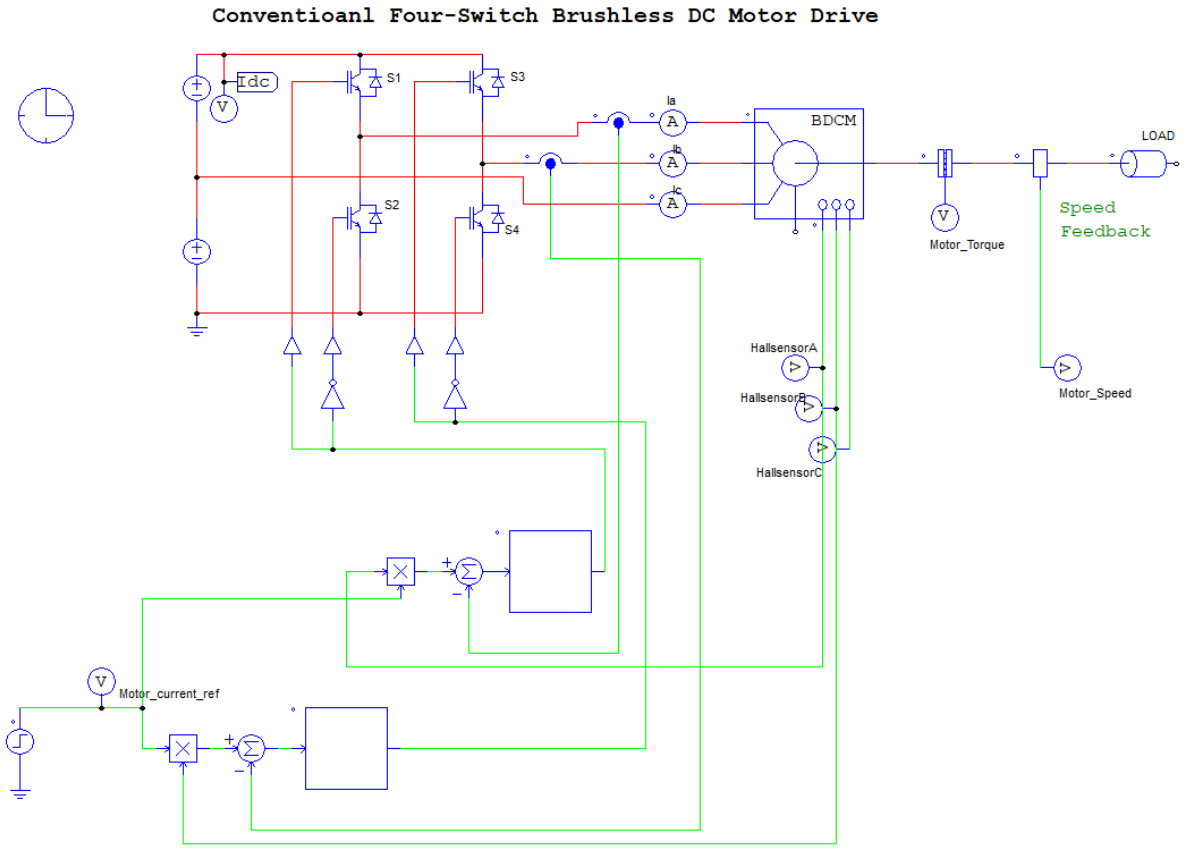
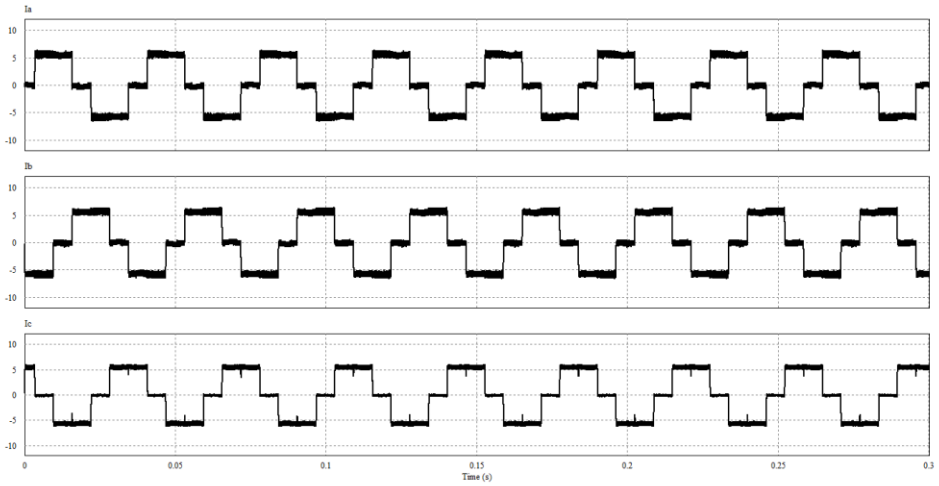


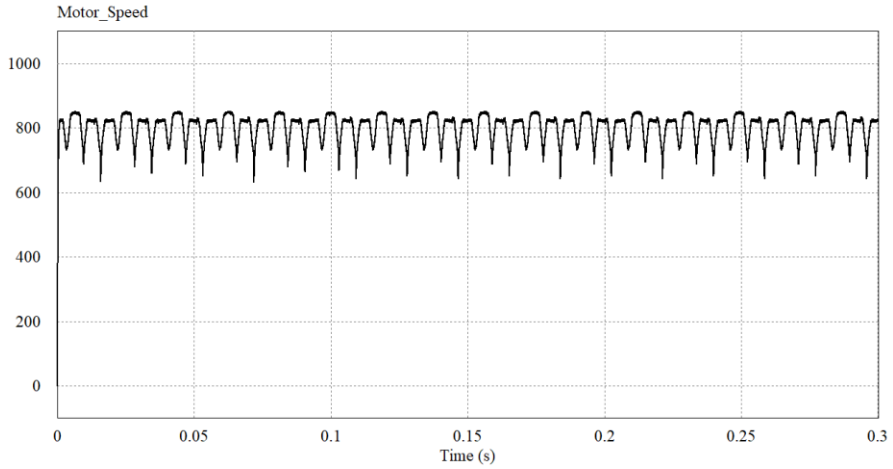
Fig. 4.3 Conventional four-switch BLDC motor drive model

Model was simulated to obtain results which are shown in Fig. 4.4. Fig. 4.2 (a) shows three phase currents of BLDC motor drive. Fig. 4.4 (b) shows motor speed. Fig. 4.4 (c) shows motor torque.

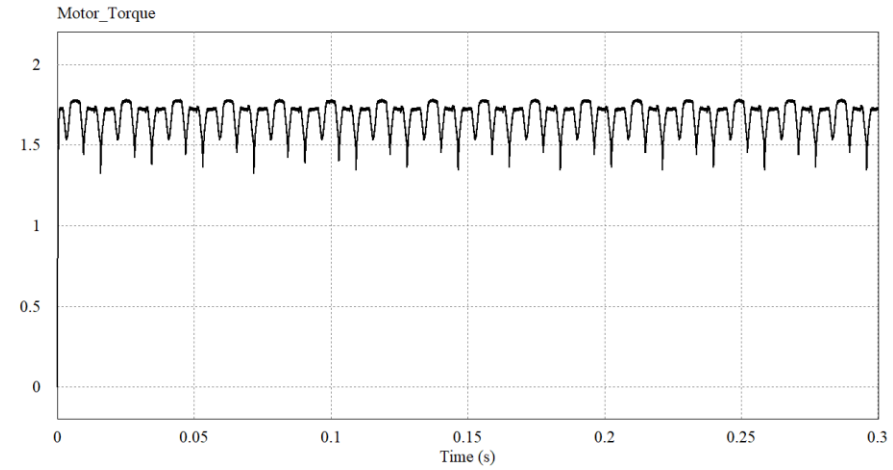
As shown in Fig. 4.4 (a), the amplitude of phase current stabilized at 5.5A and the waveform of phase current has ripple. According to Fig. 4.2 (b), the motor speed can be controlled at 800rpm. The motor torque is 1.68N·m approximately in steady state.



(a)



(b)



(c)

Fig. 4.4 Simulation results for conventional four-switch BLDC motor drive (a) Three phase currents (b) Motor speed (c) Motor torque

Comparing Fig. 4.2 and Fig. 4.4, the ripple problems of four-switch BLDC motor drive in motor speed and motor torque are more serious than six-switch BLDC motor drive. As mentioned in chapter 1, torque pulsation of the four-switch BLDC motor drive is an intrinsic problem.

4.3 Results for Six-Switch BLDC Motor Drive with Proposed System

The model of six-switch BLDC motor drive with proposed power conversion system based on control methodology shown in Fig. 3.4 was built in PSIM software, as shown in Fig. 4.5. The source DC voltage is 150V, reference voltage of the input of inverter is 400V and reference motor current is 6A.

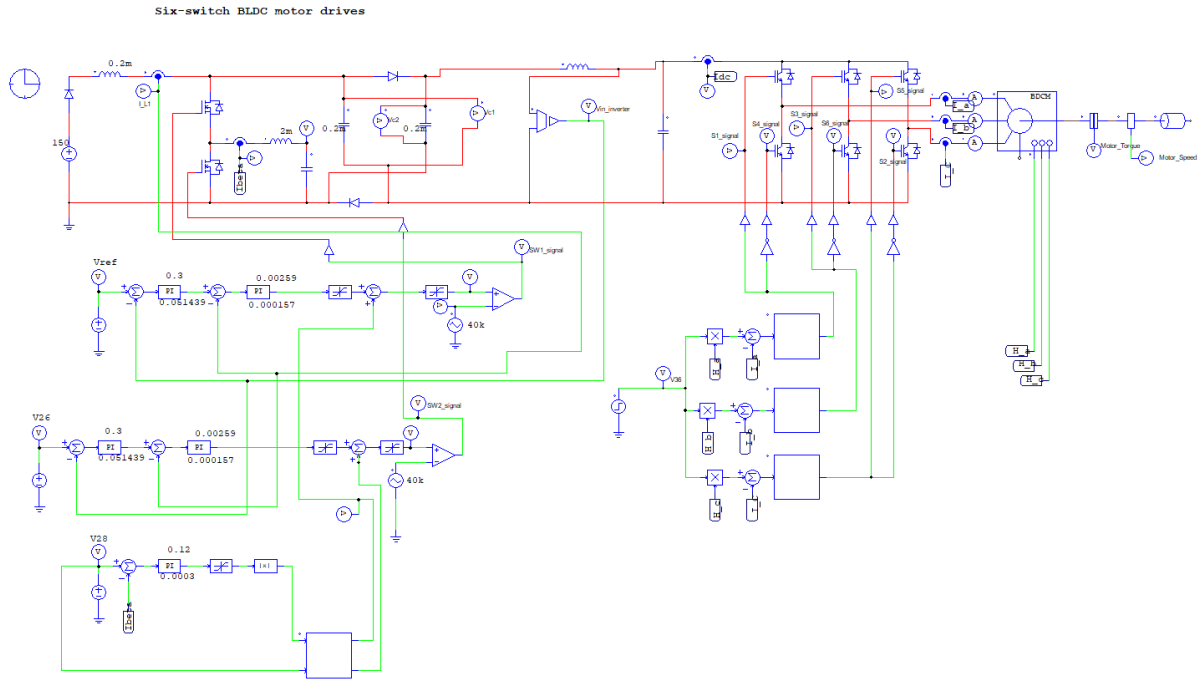


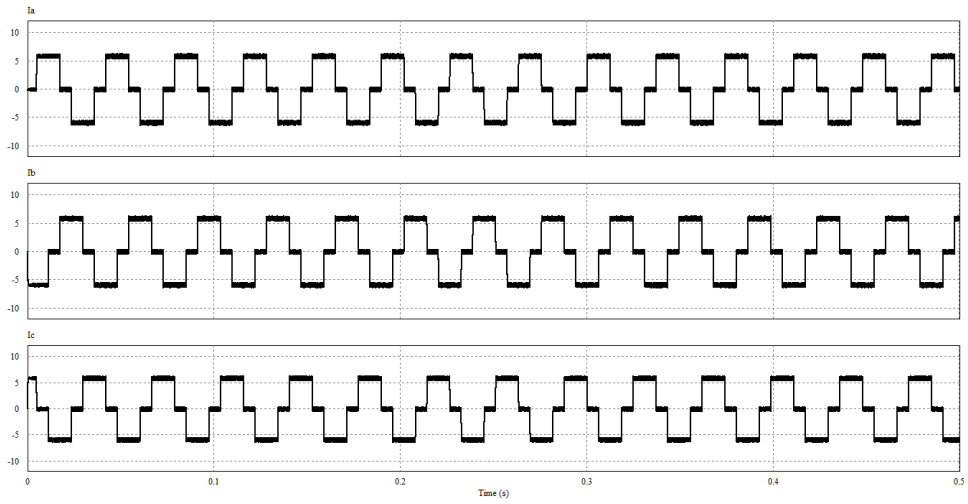
Fig. 4.5 Six-switch BLDC motor drive with proposed system

The simulation results of the developed model are shown in Fig. 4.6 and Fig. 4.7. Fig. 4.6 shows the charging mode and the reference current of energy storage is 2A. Fig. 4.7 shows the discharging mode and the reference current of energy storage is -2A. Fig. 4.6 (a) shows three phase currents. Fig. 4.6 (b) shows the motor speed. Fig. 4.6 (c) shows the motor torque. Fig. 4.6 (d) shows the input voltage of the inverter. Fig. 4.6 (e) shows the current of L_1. Fig. 4.6 (f) shows the

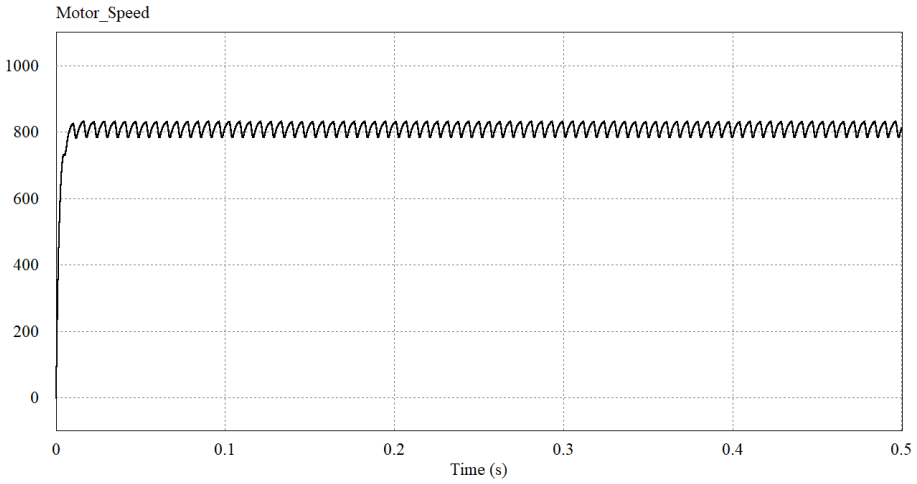
switching signals of SW_1 and SW_2. Fig. 4.6 (g) shows the switching signals of six switches of the inverter. Fig. 4.6 (h) shows the current of energy storage. The (a) ~ (h) in Fig. 4.7 show the same waveforms as (a) ~ (h) in Fig. 4.6.

It can be seen in Fig. 4.6 and Fig. 4.7 that the current, the motor speed and the motor torque can be controlled in the reference value in both charging and discharging modes. The waveforms of motor speed and motor torque reach the steady state in a short time and also have ripple. Fig. 4.6 (d) and Fig. 4.7 (d) show that the multi-purpose bi-directional DC/DC converter and diode-assisted network can boost voltage to 400V and the control system for SW_1 and SW_2 works in a good performance. Fig. 4.6 (g) and Fig. 3.7 (g) verify that SW_1 is turned on for a longer time in charging mode and SW_2 is turned on for a longer time in discharging mode. The current of energy storage can be control at 2A in charging mode and -2A in discharging mode, as shown in Fig. 4.6 (h) and Fig. 4.6(h).

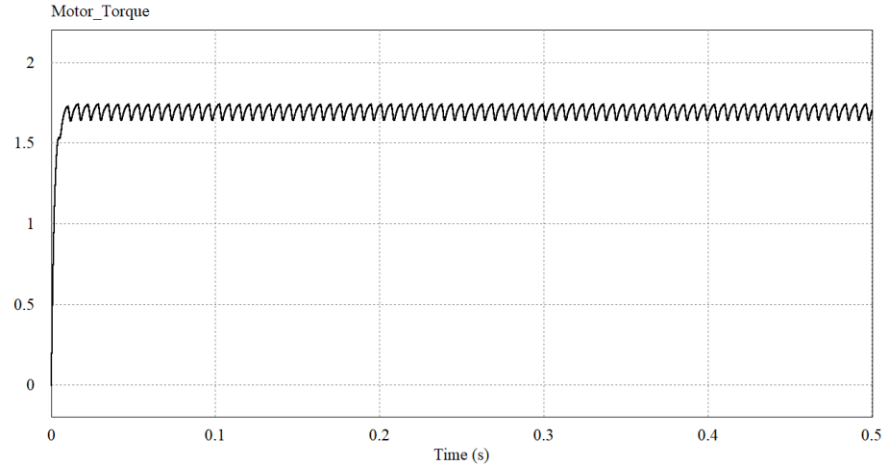
Fig. 4.6 Simulation results for six-switch BLDC motor drive with proposed system in charging mode (a) Three phase currents (b) Motor speed (c) Motor torque (d) input voltage of inverter (e) L_1 current (f) Switching signals of SW_1 and SW_2 (g) Switching signals of six switches of inverter (h) Current of energy storage


Ia
Ib
Ic
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
Time (s)

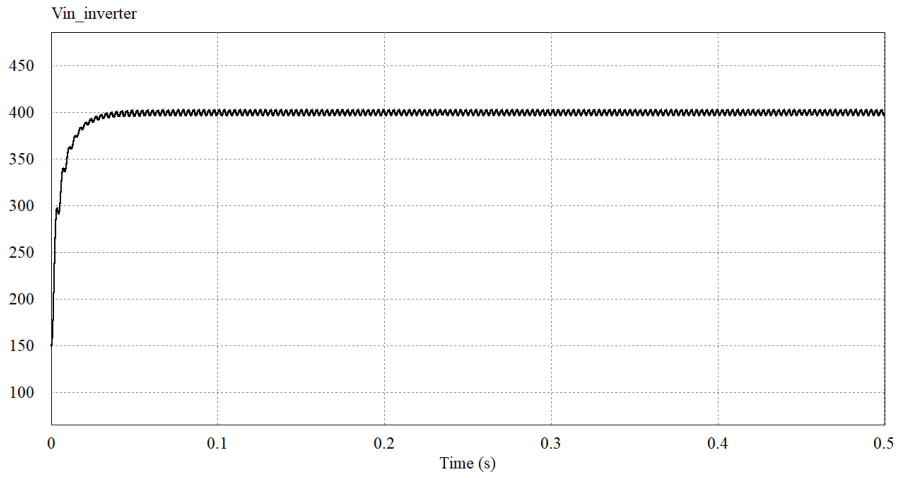
(a)


Motor_Speed
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

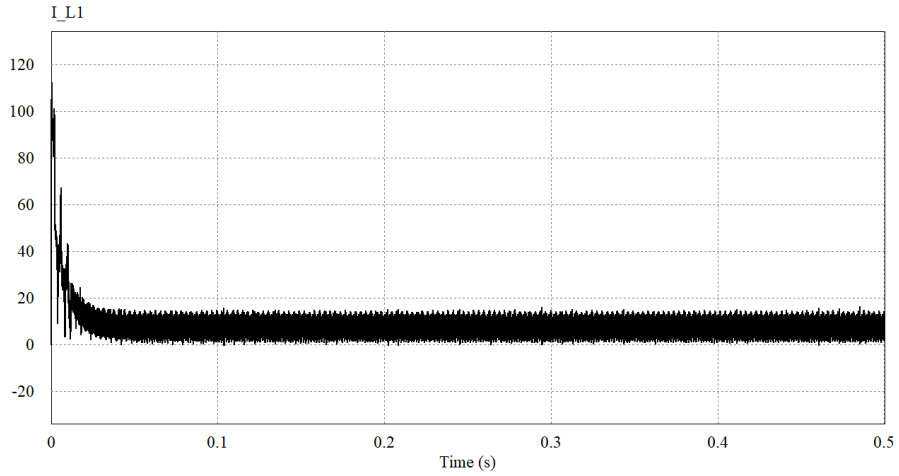
(b)


Motor_Torque
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

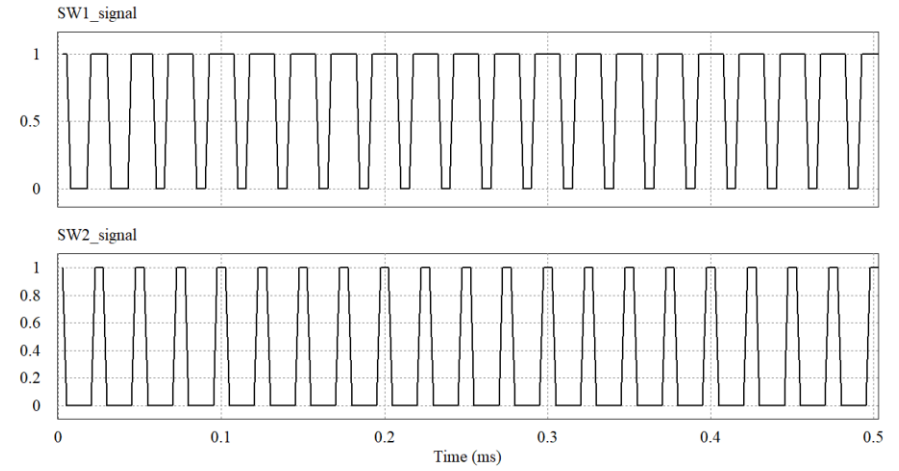
(c)


Vin_inverter
450
400
350
300
250
200
150
100
0
0.1
0.2
0.3
0.4
0.5
Time (s)

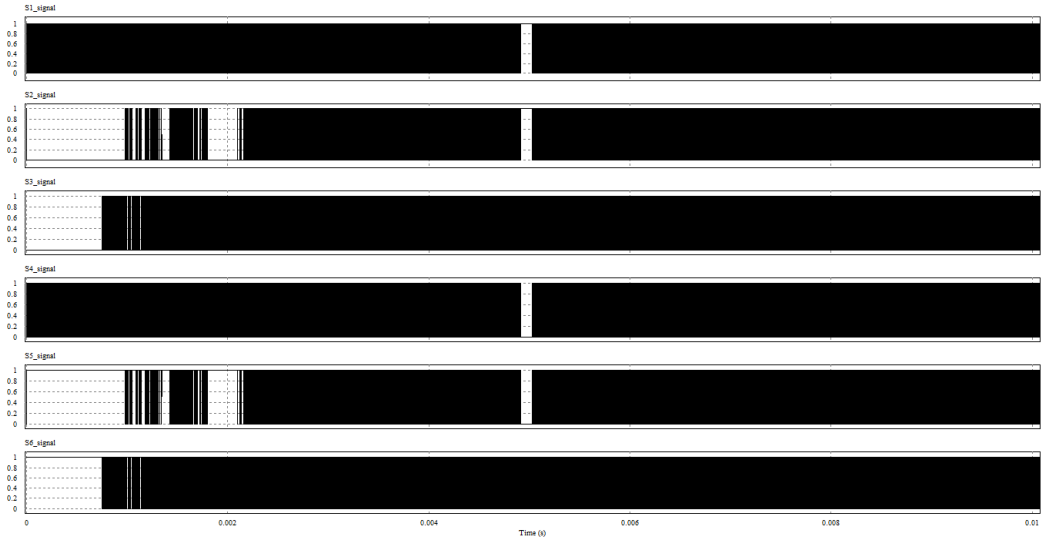
(d)


I_L1
120
100
80
60
40
20
0
-20
0
0.1
0.2
0.3
0.4
0.5
Time (s)

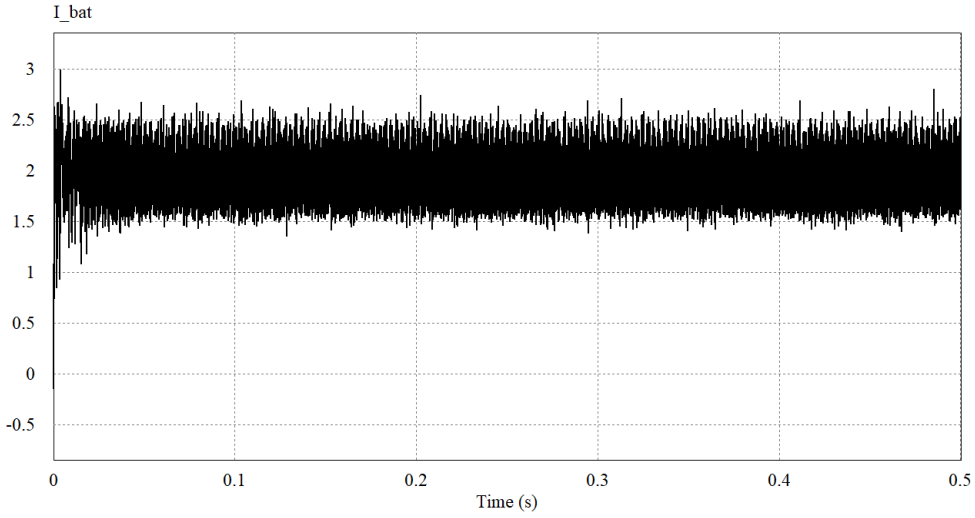
(e)


SW1_signal
1
0.5
0
SW2_signal
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
Time (ms)

(f)

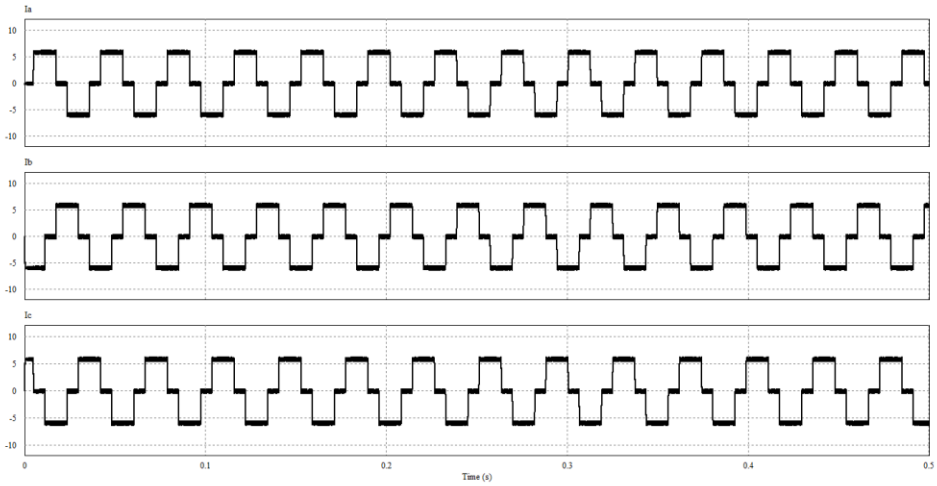

S1_signal
S2_signal
S3_signal
S4_signal
S5_signal
S6_signal
0
0.002
0.004
0.006
0.008
0.01
Time (s)

(g)

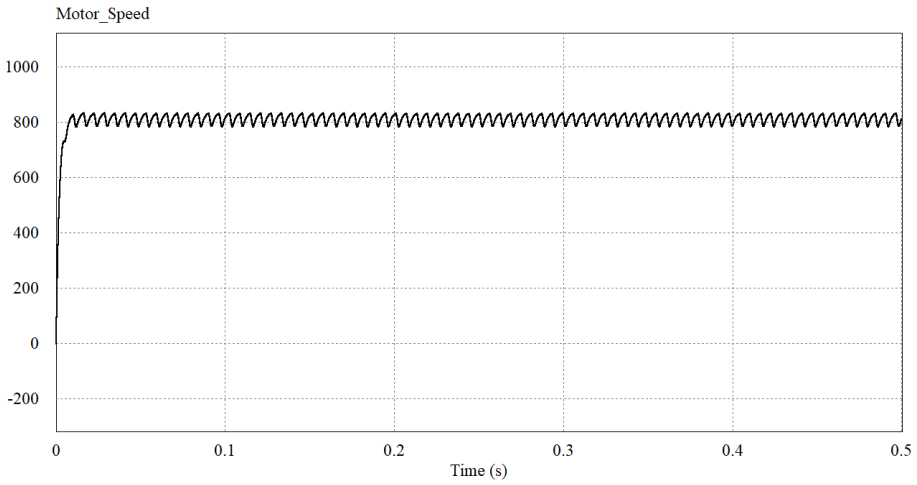

I_bat
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5
Time (s)

(h)

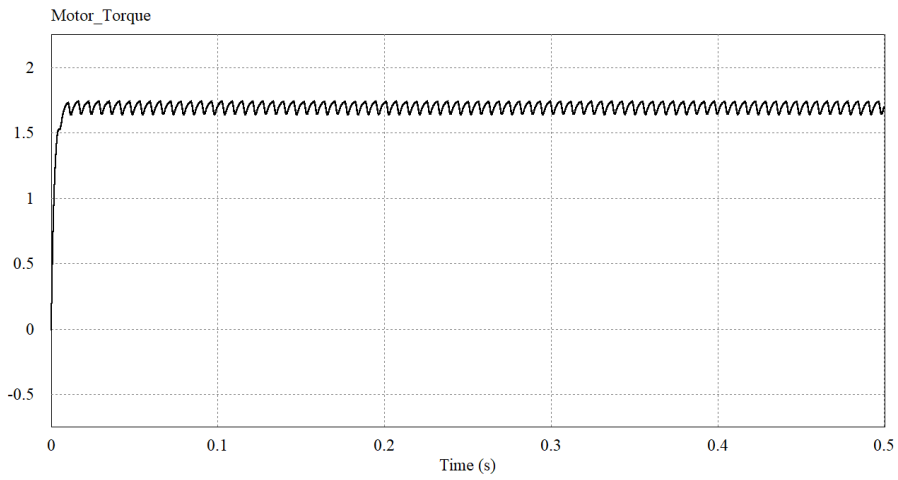
Fig. 4.7 Simulation results for six-switch BLDC motor drive with proposed system in discharging mode (a) Three phase currents (b) Motor speed (c) Motor torque (d) input voltage of inverter (e) L_1 current (f) Switching signals of SW_1 and SW_2 (g) Switching signals of six switches of inverter (h) Current of energy storage


Ia
Ib
Ic
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
Time (s)

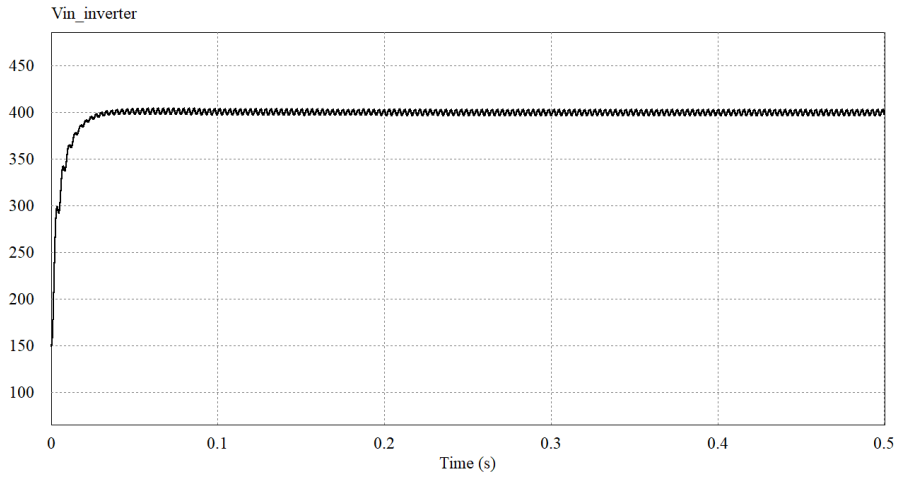
(a)


Motor_Speed
1000
800
600
400
200
0
-200
0
0.1
0.2
0.3
0.4
0.5
Time (s)

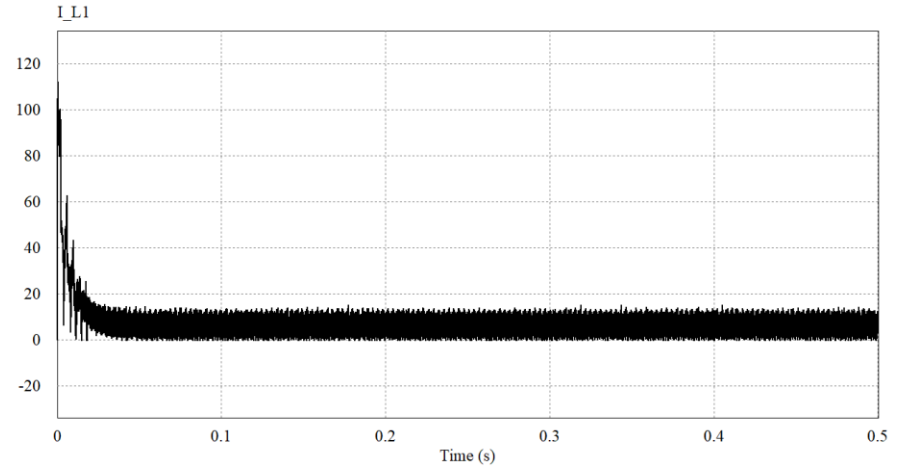
(b)


Motor_Torque
2
1.5
1
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5
Time (s)

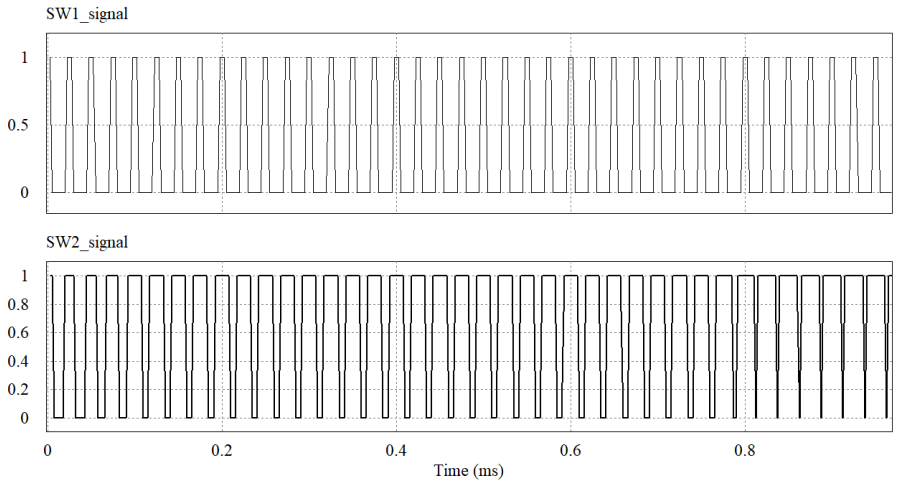
(c)


Vin_inverter
450
400
350
300
250
200
150
100
0
0.1
0.2
0.3
0.4
0.5
Time (s)

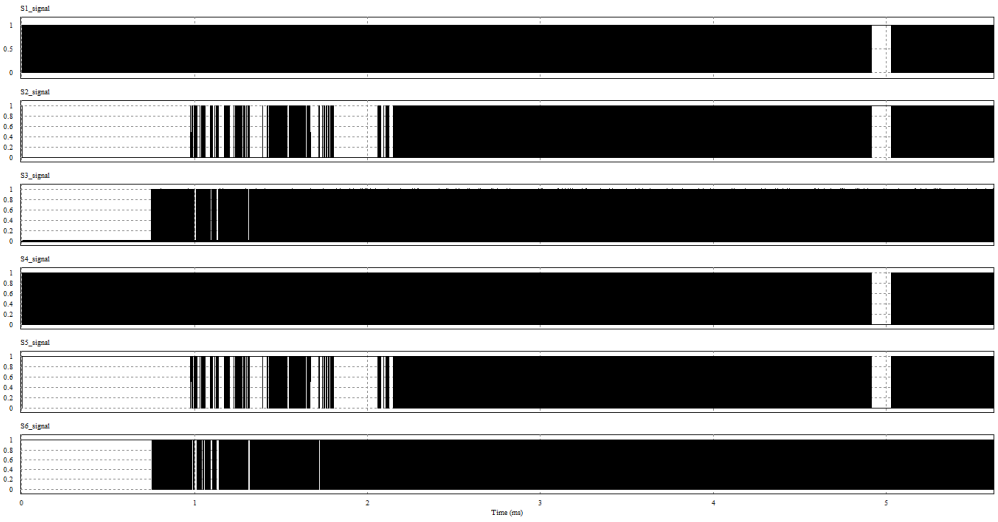
(d)


I_L1
120
100
80
60
40
20
0
-20
0
0.1
0.2
0.3
0.4
0.5
Time (s)

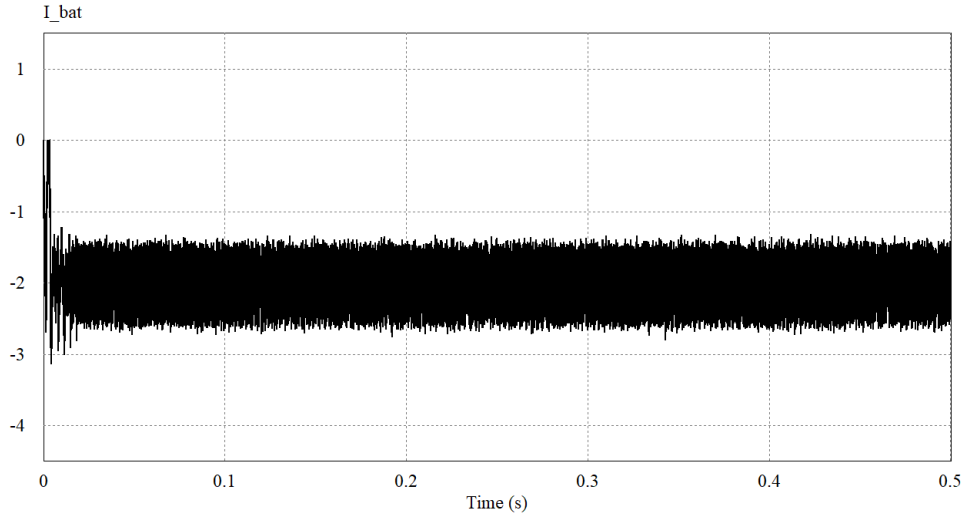
(e)


SW1_signal
1
0.5
0
SW2_signal
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
Time (ms)

(f)



(g)



(h)

4.4 Results for Four-Switch BLDC Motor Drive with Proposed System

The model of four-switch BLDC motor drive with proposed power conversion system based on control methodology shown in Fig. 3.4 was built in PSIM software, as shown in Fig. 4.8. The source DC voltage is 150V, reference voltage of the input of inverter is 400V and reference motor current is 6A.

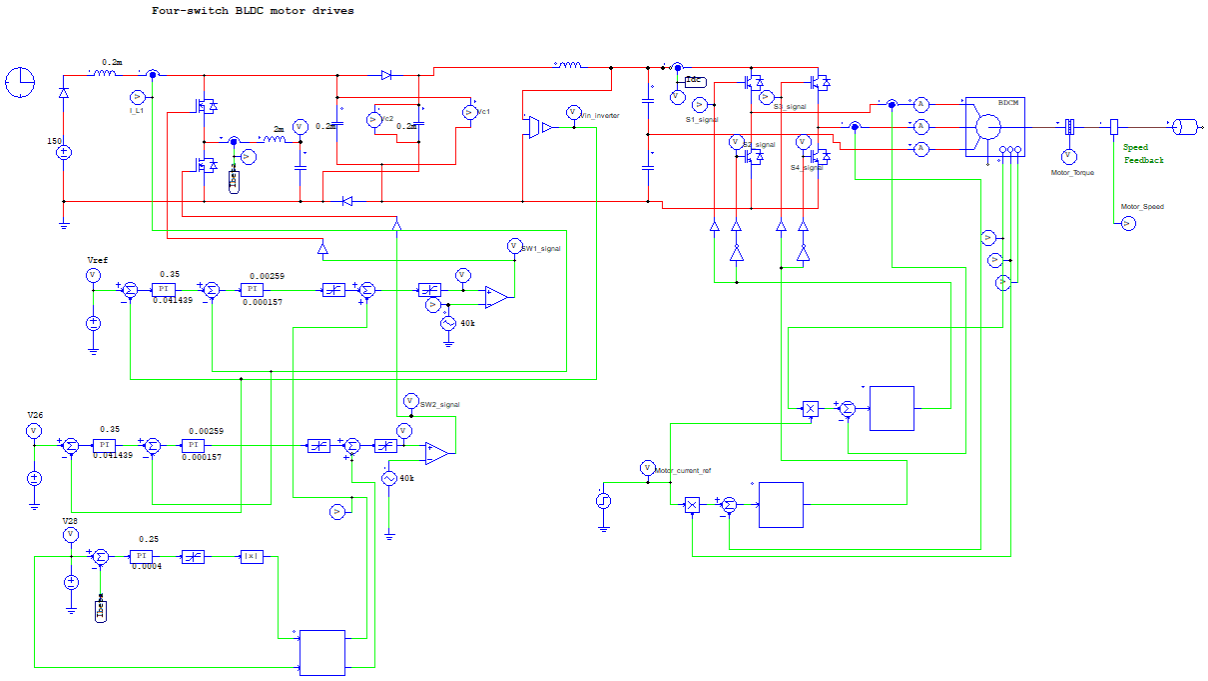
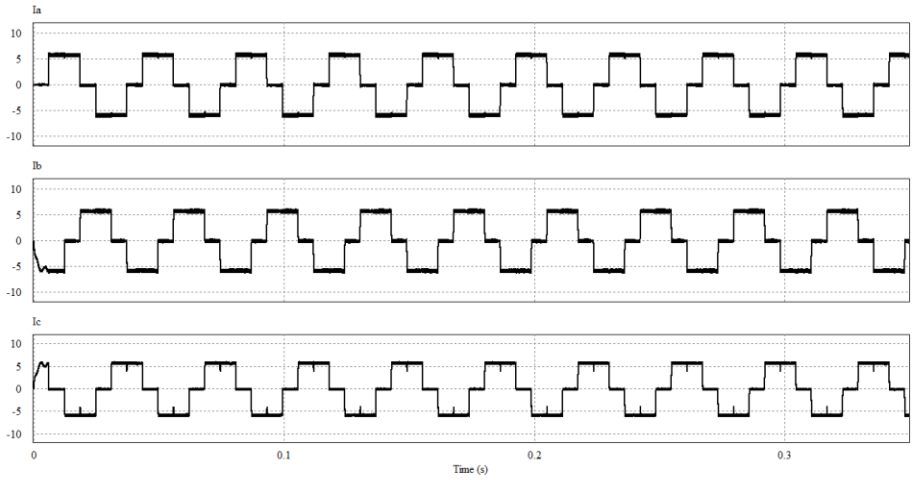


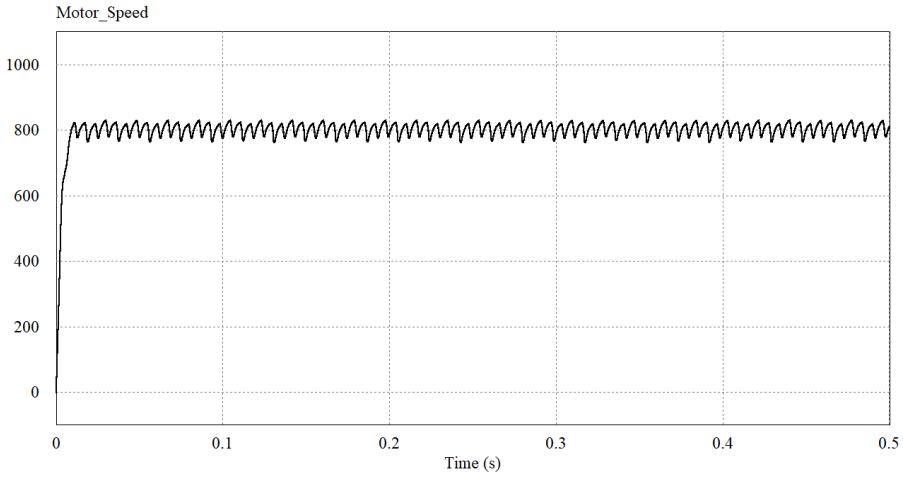
Fig. 4.8 Four-switch BLDC motor drive with proposed system

The simulation results are also divided into charging mode and discharging mode and shown in Fig. 4.9 and Fig. 4.10. The (a) ~ (h) in Fig. 4.9 and Fig. 4.10 show the same waveforms as (a) ~ (h) in Fig. 4.6.

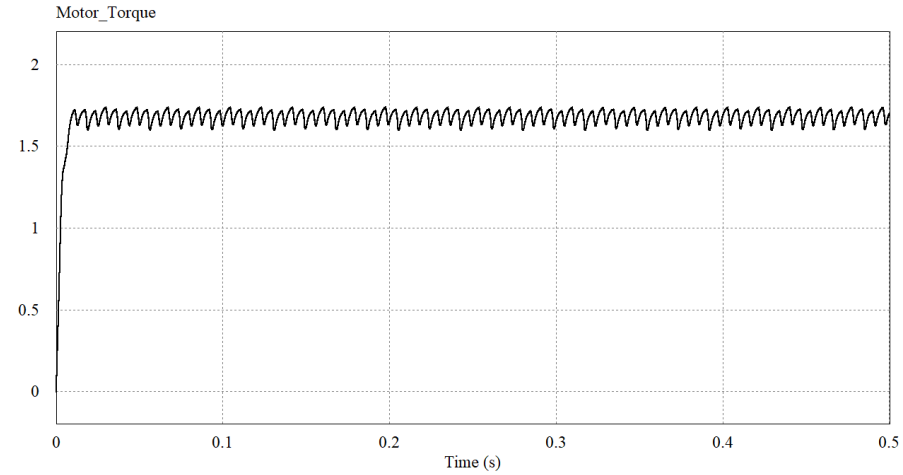
Fig. 4.9 Simulation results for four-switch BLDC motor drive with proposed system in charging mode (a) Three phase currents (b) Motor speed (c) Motor torque(d) input voltage of inverter (e) L_1 current (f) Switching signals of SW_1 and SW_2 (g) Switching signals of four switches of inverter (h) Current of energy storage


Ia
10
5
0
-5
-10
Ib
10
5
0
-5
-10
Ic
10
5
0
-5
-10
0
0.1
0.2
0.3
Time (s)

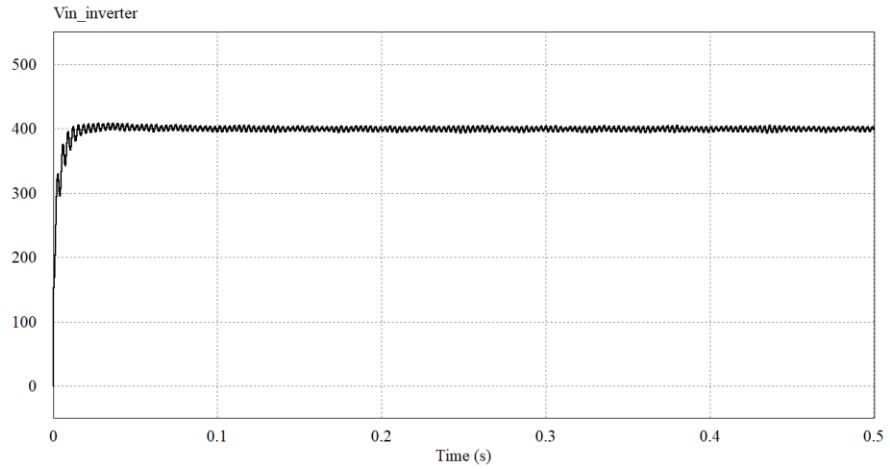
(a)


Motor_Speed
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

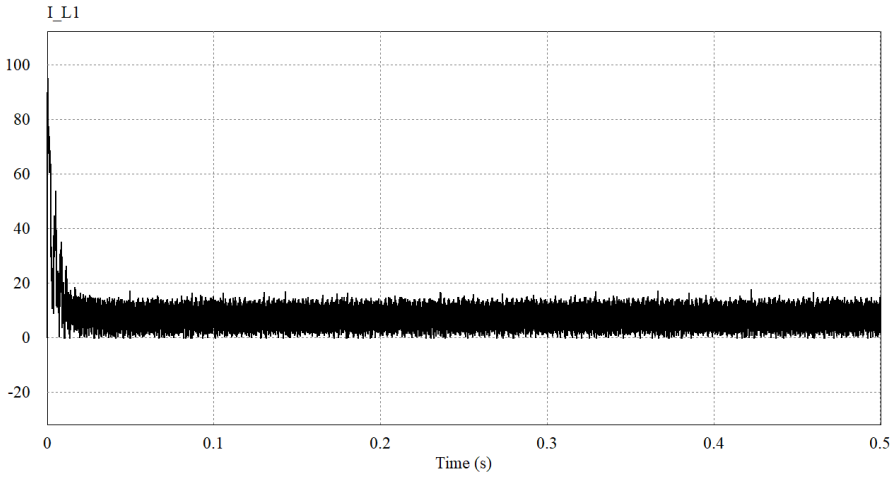
(b)


Motor_Torque
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

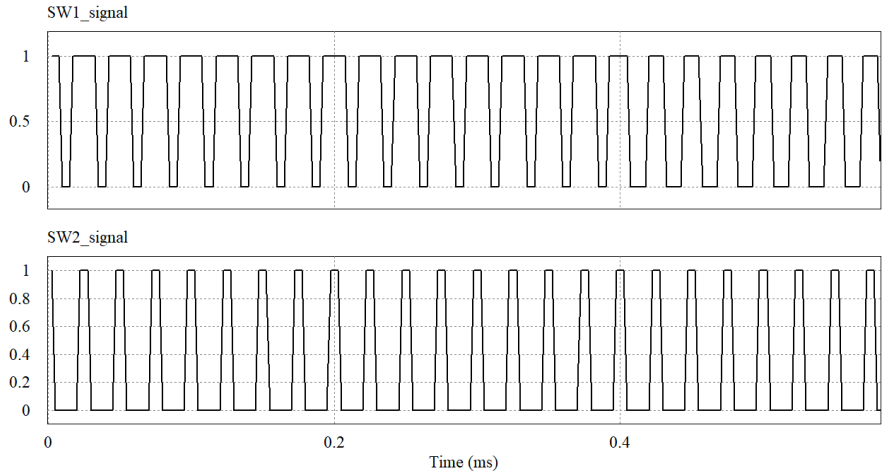
(c)


Vin_inverter
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

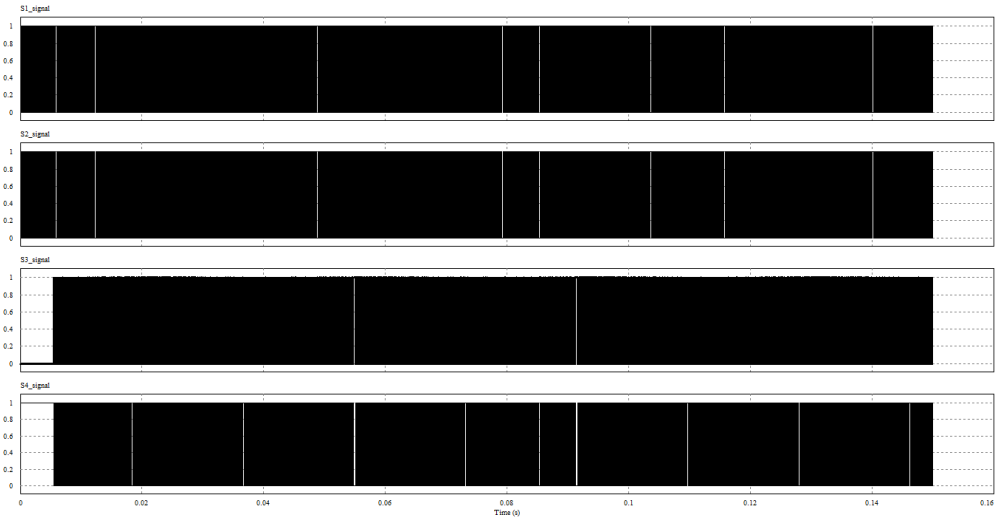
(d)


I_L1
100
80
60
40
20
0
-20
0
0.1
0.2
0.3
0.4
0.5
Time (s)

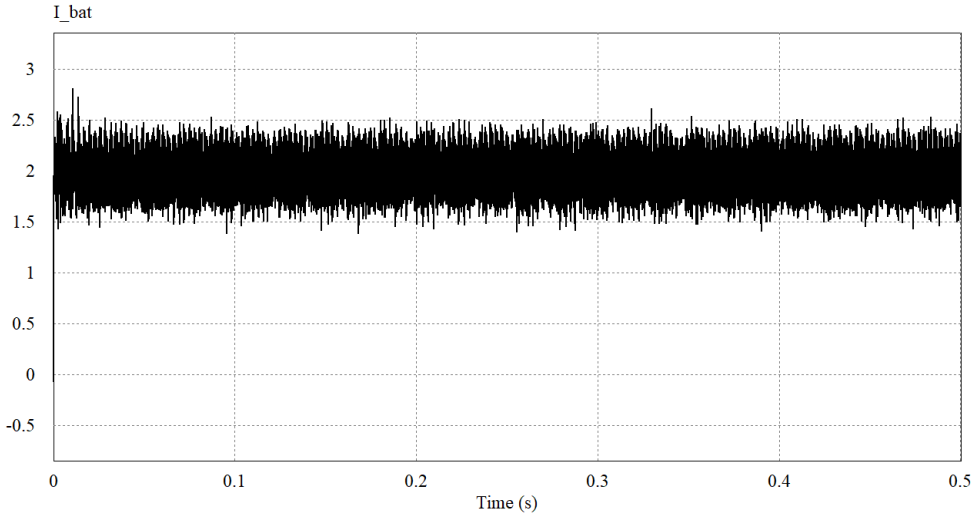
(e)


SW1_signal
1
0.5
0
SW2_signal
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
Time (ms)

(f)

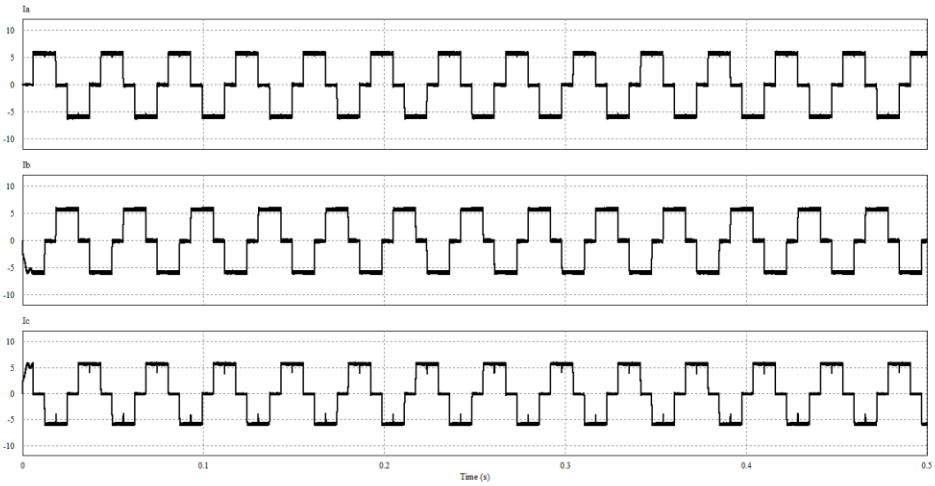

S1_signal
S2_signal
S3_signal
S4_signal
Time (s)

(g)

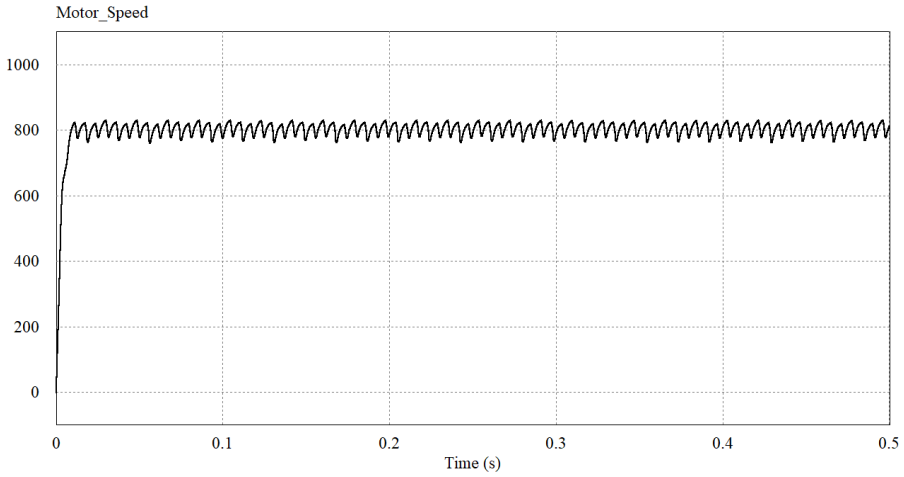

I_bat
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5
Time (s)

(h)

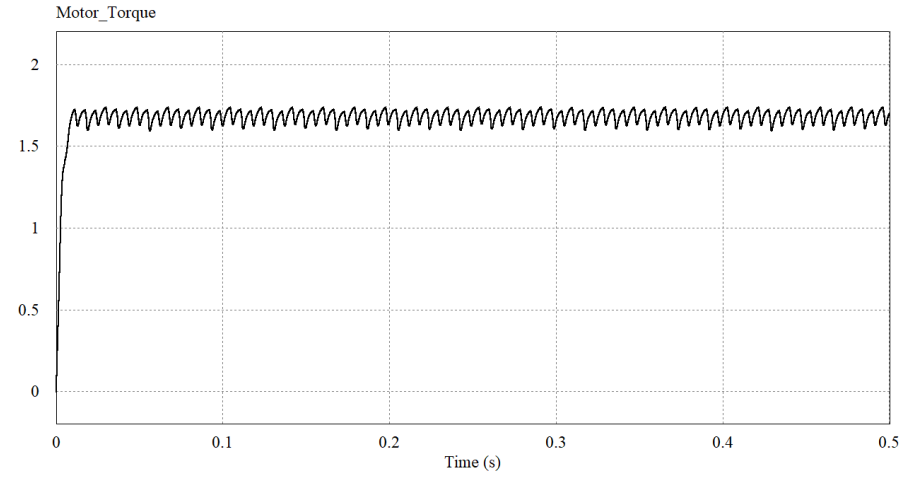
Fig. 4.10 Simulation results for four-switch BLDC motor drive with proposed system in discharging mode (a) Three phase currents (b) Motor speed (c) Motor torque (d) input voltage of inverter (e) L_1 current (f) Switching signals of SW_1 and SW_2 (g) Switching signals of four switches of inverter (h) Current of energy storage


Ia
Ib
Ic
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
Time (s)

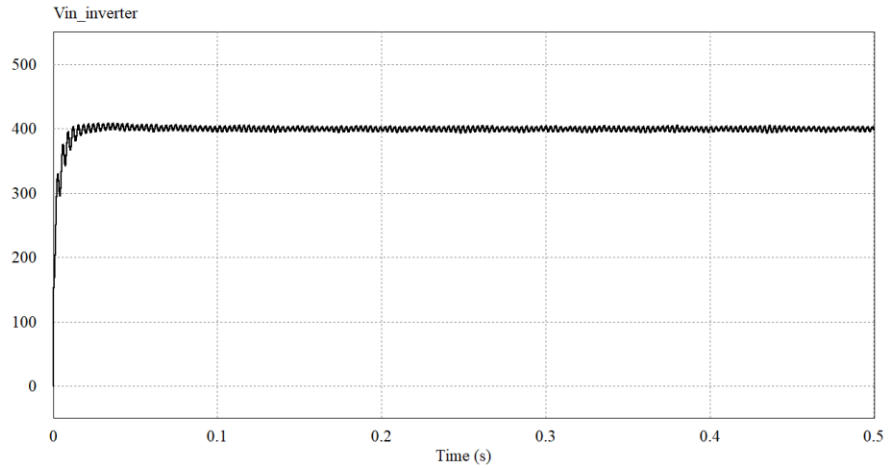
(a)


Motor_Speed
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

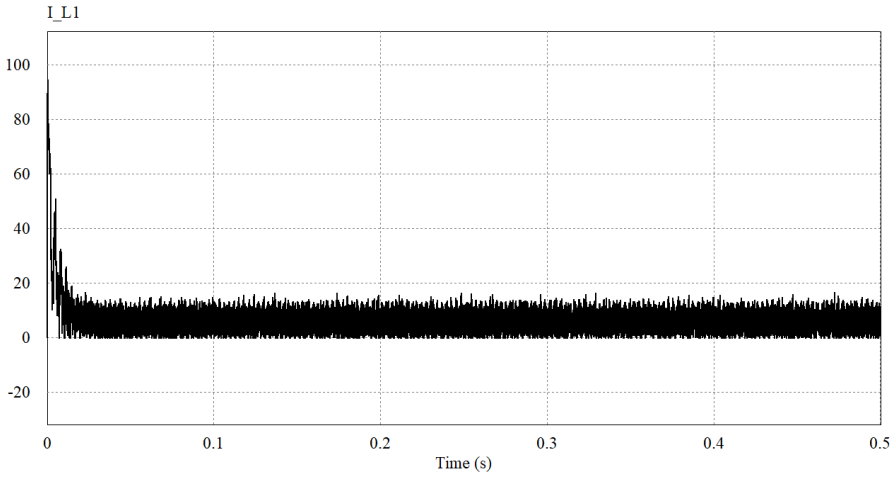
(b)


Motor_Torque
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

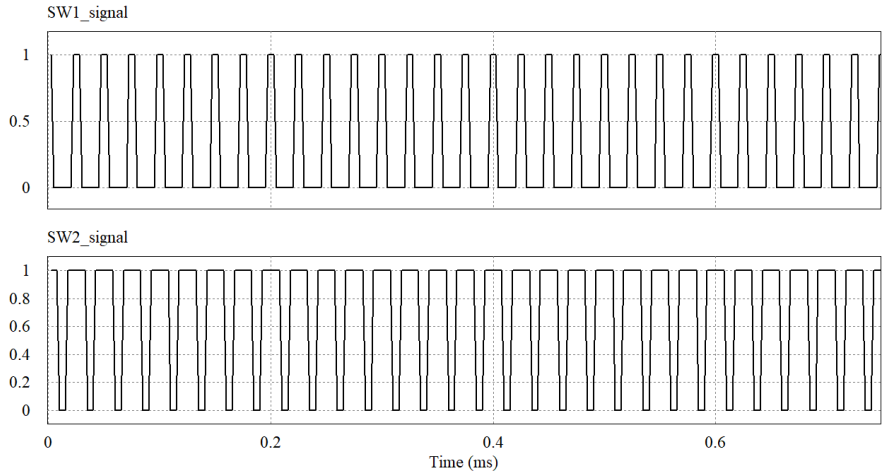
(c)


Vin_inverter
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
Time (s)

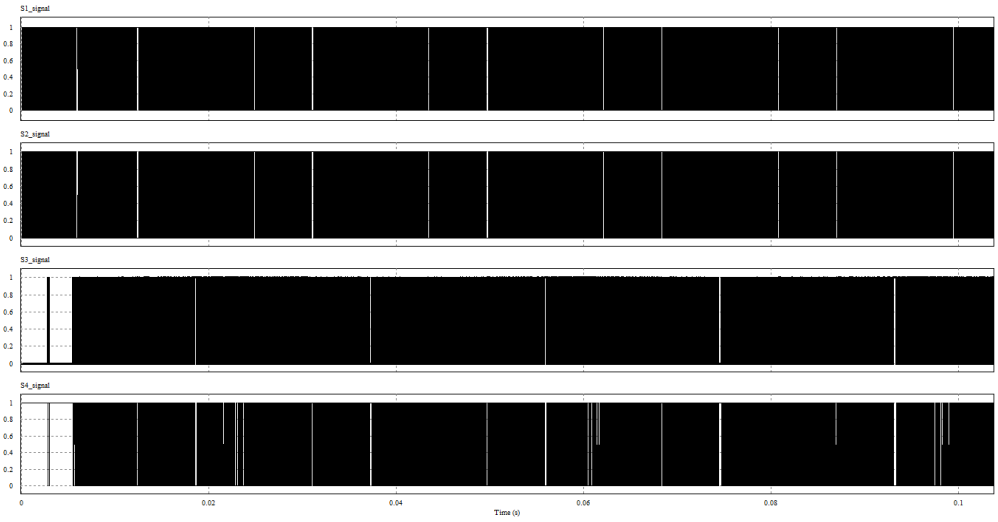
(d)


I_L1
100
80
60
40
20
0
-20
0
0.1
0.2
0.3
0.4
0.5
Time (s)

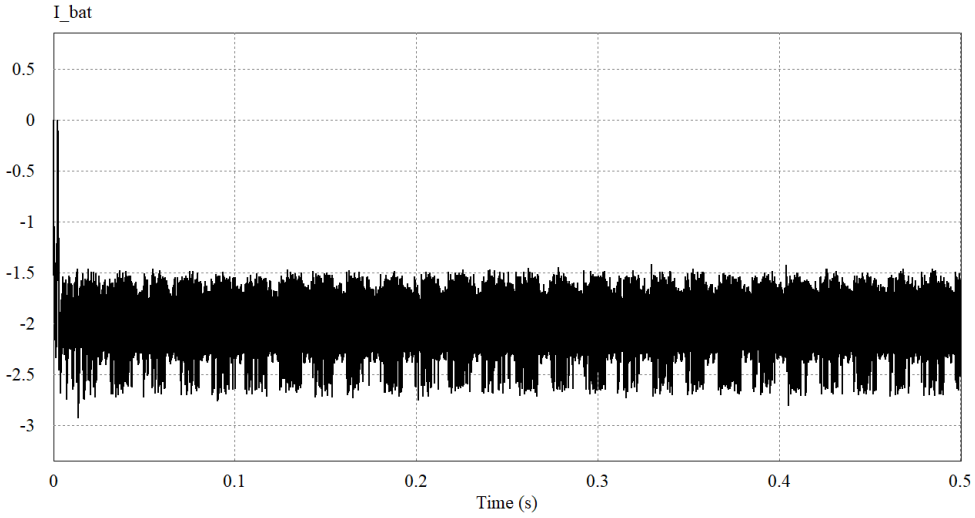
(e)


SW1_signal
1
0.5
0
SW2_signal
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
Time (ms)

(f)



(g)



(h)

In four-switch BLDC motor drive, the proposed power conversion system also works well. The phase currents, motor speed, motor torque and input voltage of inverter also can be controlled at the command value. Fig. 4.11 shows the detailed phase currents. Based on the simulation results, torque ripple is calculated for four models and tabulated in Table 4.1.

As shown in Fig. 4.11, when phase *a* and phase *b* are activated, the current is increased more than other modes due to the supply of full DC-link voltage in mode II and mode V.

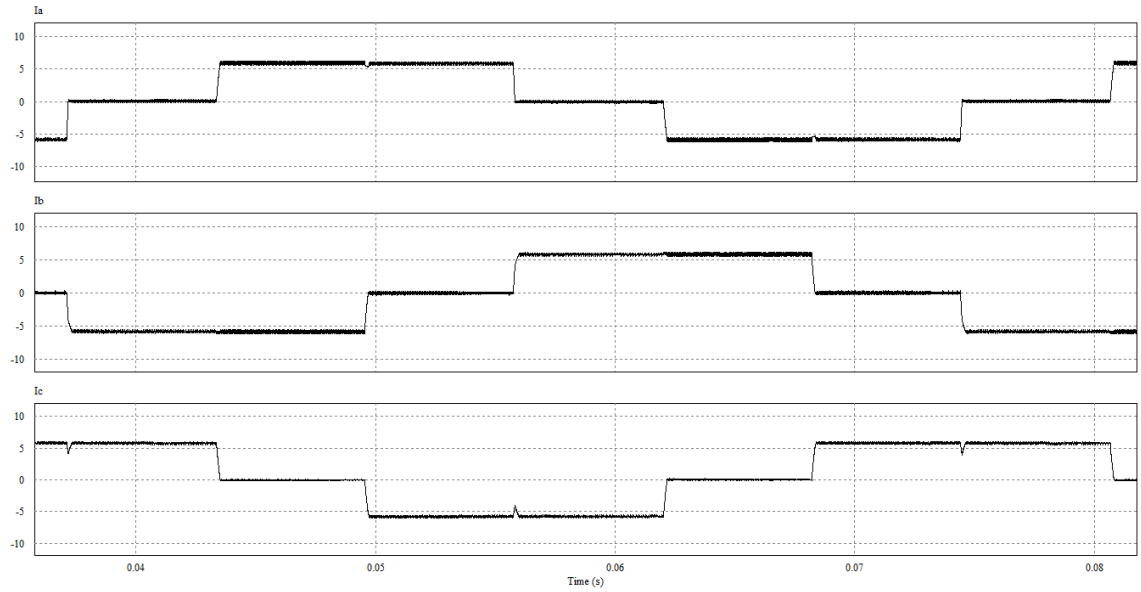


Fig. 4.11 Detailed phase currents

Table 4.1 Torque ripple for four models

Models	Peak to Peak Torque Ripple
Conventional six-switch BLDC motor drive	0.10489
Conventional four-switch BLDC motor drive	0.45962
Six-switch BLDC motor drive with proposed system	0.10145
Four-switch BLDC motor drive with proposed system	0.13921

From Table 4.1, the proposed power conversion system has a little bit improvement for reducing torque ripple of six-switch BLDC motor drive. Moreover, for the four-switch BLDC motor drive, the proposed system can reduce the torque ripple obviously.

Chapter 5 Conclusion

Based on the simulation done in this thesis work, it can be concluded that the proposed power conversion system can work in a good performance. The proposed power conversion system can increase the voltage boosting ratio based on the diode-assisted network structure compared to conventional boost converters. The bi-directional DC/DC converter configuration in the proposed system can boost the input voltage and charge/discharge energy storage simultaneously. The proposed system with the energy storage can support power to motor drive reducing torque pulsation. The proposed structure and control strategy are verified by the PSIM simulations.

This research work was based on theory and simulation. Thus, using real time simulator like OPAL-RT with HIL (hardware in the loop) for further study with this advanced power conversion system for six-switch and four-switch BLDC motor drive will be the future work. In addition, the control methods used in this system could be replaced by some more useful and practicable methods, such as space vector control. A deeply study for control would be the future work too.

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