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Advanced Power Conversion System for Motor Drive in Electrified Vehicles.

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Abstract: *This paper presents a power conversion system for six-switch BLDC motor drive and fourswitch 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.*

Keywords: Electric Vehicle, BLDC Motor, PI Controller, PSIM Software

I. Introduction

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 includes “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, 2 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.

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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.

II. Six-Switch and Four-Switch BLDC Motor Drives

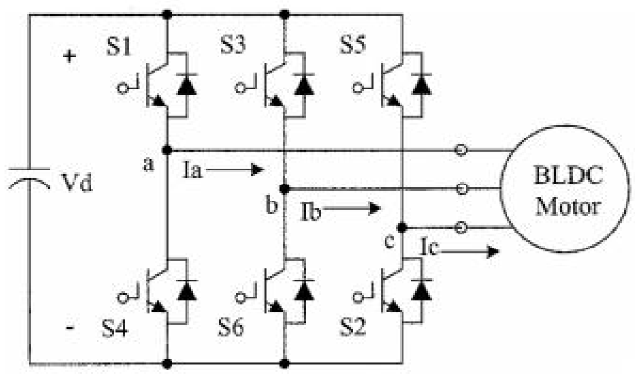

Figure 1: Six-switch BLDC motor drive system

Fig. 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

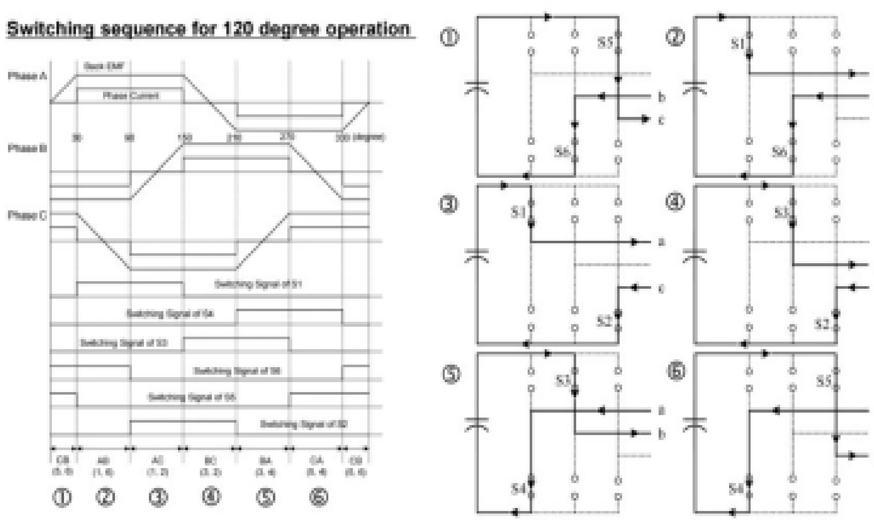

Figure 2: Switching sequences for six-switch BLDC motor drive

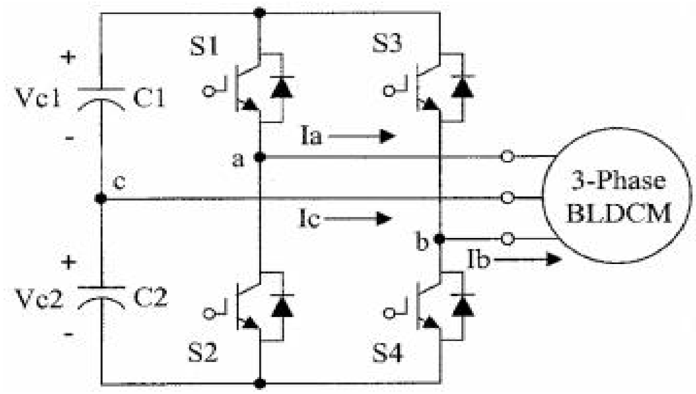

Figure 3: Four-switch BLDC motor drive system

Fig. 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.

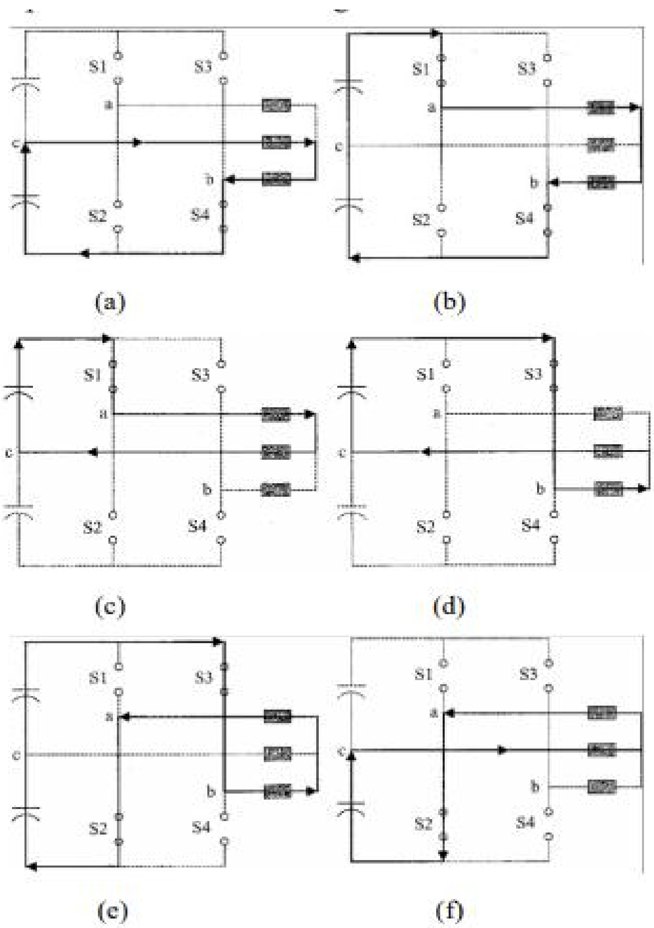

Figure 4: Switching sequences for four-switch BLDC motor drive

Table 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.4 and Table 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 Ib is zero. Mode III can be divided in two sub-modes, In this mode, switch S1 is turned on for supplying DC-link voltage to increase current. when S1 is turned on, Ia increase and Ic = -(Ia + Ib) = -Ia (Ib = 0). When Ia reaches the upper limit, S1 is turned off and the current flows through D2 (diode of S2), as shown in Fig.2.5(b). Thus, Ia 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 S1 and S4 are turned on to increase the current; when S1 and S4 are turned off, the current will flow through D2 and D3 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.

III. PROPOSED SIX-SWITCH BLDC SYSTEM

Based on the study and methods mentioned above, 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. 5

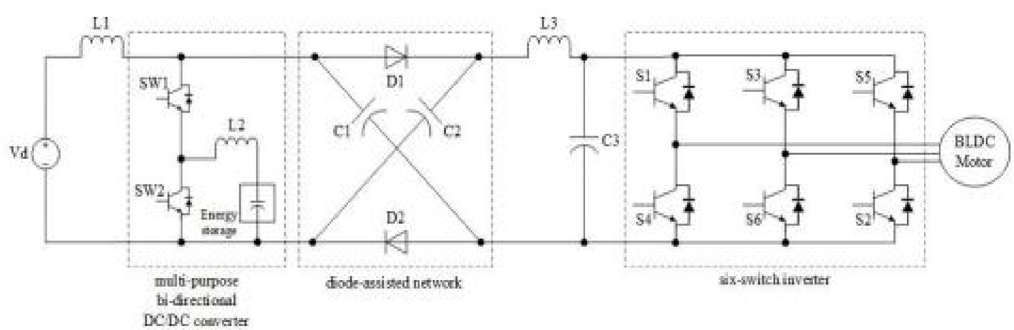

Figure 5: System diagram for proposed system with six-switch BLDC motor drive

As shown in Fig. 5, 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 (SW1 and SW2) of multi-purpose bi-directional DC/DC converter.

IV. 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. 6.

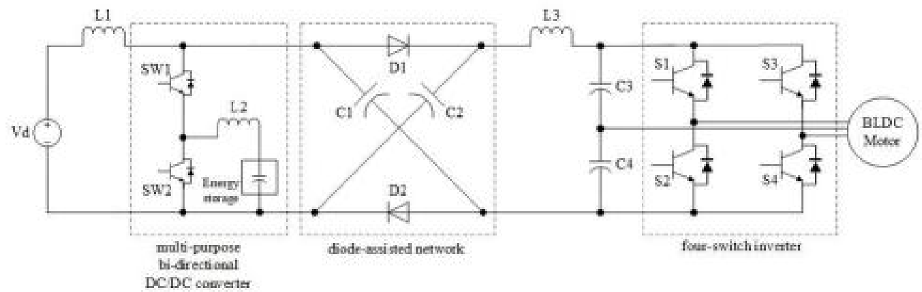

Figure 6: System diagram for proposed system with four-switch BLDC motor drive

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.

V. 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.

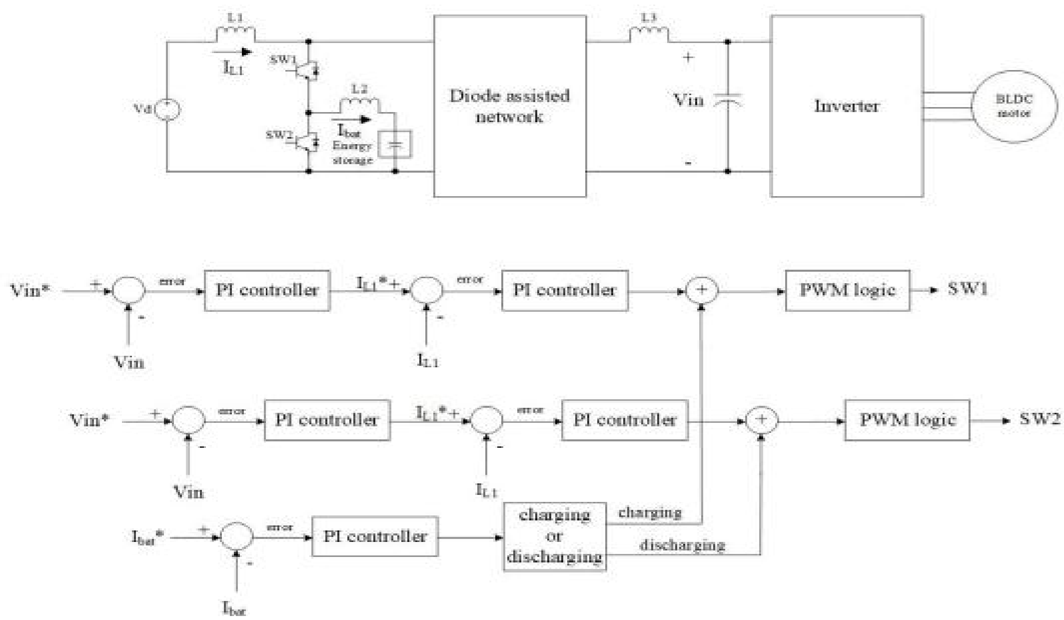

Figure 7: Diagram of the control system for switches in DC/DC converter

The input voltage of the inverter is used as benchmark to control switches in the DC/DC converter (SW1 and SW2). 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, SW1 and SW2 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. 7

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VI. Simulation Study And Discussion

Conventional six-switch BLDC motor drive was developed and simulated in PSIM software. The developed model is shown in Fig. 8 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.

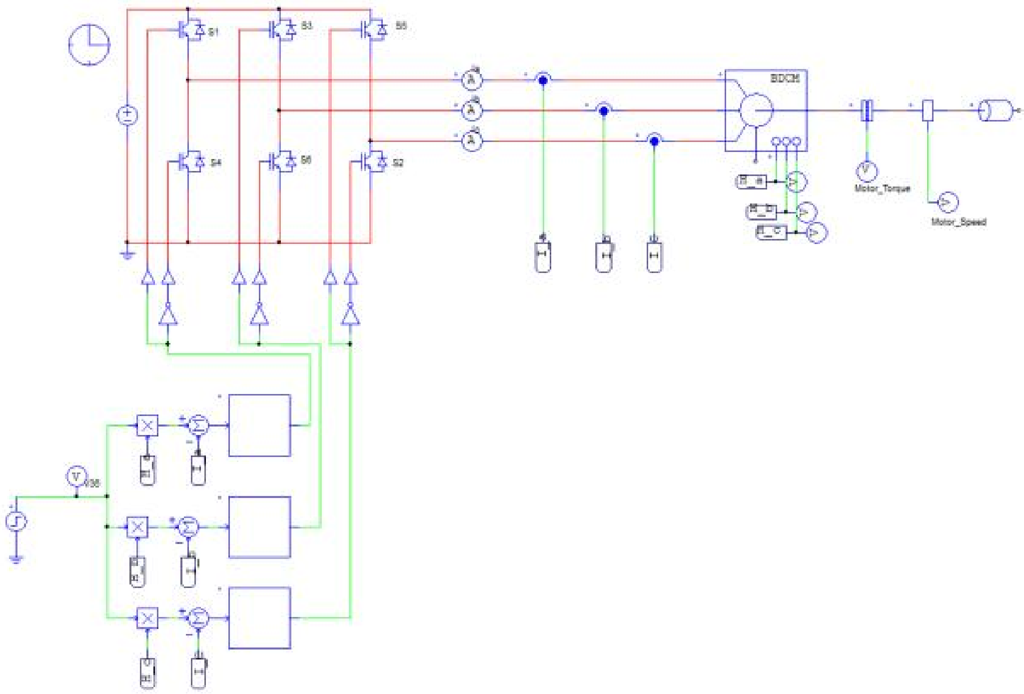

Figure 8: Conventional six-switch BLDC motor drive model

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. 9. The source DC voltage is 150V, reference voltage of the input of inverter is 400V and reference motor current is 6A.

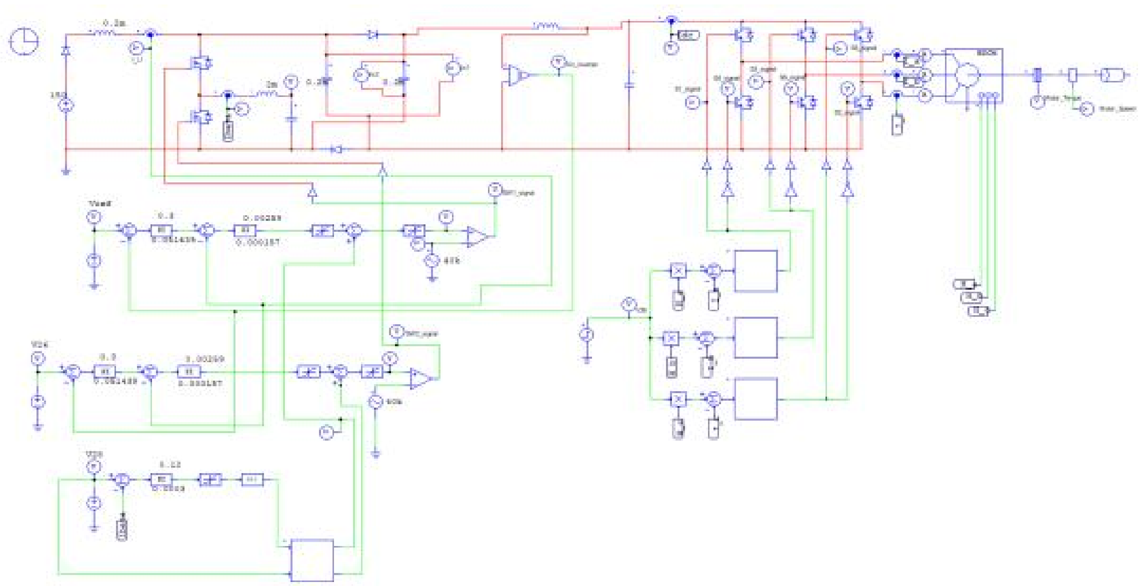

Figure 9: Six-switch BLDC motor drive with proposed system

VII. Conclusion

Based on the simulation done in this paper, 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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