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Four Switch Three Phase Brushless DC Motor Drive for Hybrid Vehicles

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ABSTRACT: This paper proposes a low cost four-switch brushless dc (BLDC) motor drive for driving hybrid electric vehicles. A two input dc-dc boost converter is proposed that interfaces a unidirectional photo voltaic (PV) input power port and a bidirectional battery port as a storage element in a unified structure. The two input dc-dc boost converter supplies the regulated voltage to four-switch BLDC drive. For effective utilization of the four switch three phase BLDC motor drive direct current controlled PWM scheme is designed and implemented to produce the desired dynamic and static speed-torque characteristics. Speed limitation is a major problem of four switch topology. This problem is solved by regulating the output voltage of two input dc-dc boost converter.

KEYWORDS: Brushless DC (BLDC) motor drive, four-switch three-phase inverter, photovoltaic/battery hybrid power system.

1. INTRODUCTION

The demand of BLDC motor drive is increasing nowadays, because of its high power density, high torque, high efficiency, etc. Hence it is commonly used in electric vehicles. The importance of hybrid electric vehicle is inevitable in the present scenario. Hybrid electric vehicle uses more than one electric power sources such as photovoltaic cell, battery, wind energy etc. One of the biggest disadvantages of renewable energy source such as photo voltaic energy, wind energy etc. is that the energy supply is not constant; it depends on weather and other natural phenomenon [5]. So a reliable backup system such as battery is necessary to provide un-interrupted and stable power supply. In these systems with a storage element such as battery, the bidirectional power flow capability is a key feature at the storage port. In addition to that, the input power sources should have the ability of supplying the load individually and simultaneously with the storage element [2].

Electronic commutation is used to control BLDC motors; it makes the drive costlier when comparing with other electric motors. Conventionally for a three phase BLDC motor six switches are used to drive the motor, as shown in Fig.

1. Nowadays many studies are focusing on how to reduce the cost of BLDC motor drive [3], [4]. Four switch topology is away to reduce the cost of three phase BLDC drive; where it reduces the number of switch by two [6], as shown in Fig.

2. The main drawback of the four switch topology is speed limitation of BLDC motor. A conventional four switch BLDC drive can operate only up to half of the rated speed.

By combining two input dc-dc boost converter with four switch BLDC drive topology, a low cost three phase BLDC drive can be formed for hybrid electric vehicle. Two input dc-dc boost converter is used to supply the voltage to four switch converter. By regulating the output voltage of two input dc-dc boost converter according to the speed of BLDC motor; the motor can run up to rated speed.

II. FOUR SWITCH THREE PHASE BLDC DRIVE

In four switch topology, four switches are used instead of six and one phase is directly connected to the common point of dc-dc capacitor. The topology is shown in Fig. 2. The desired back-emf and current profiles for three-phase BLDC motor is shown in Fig. 3.

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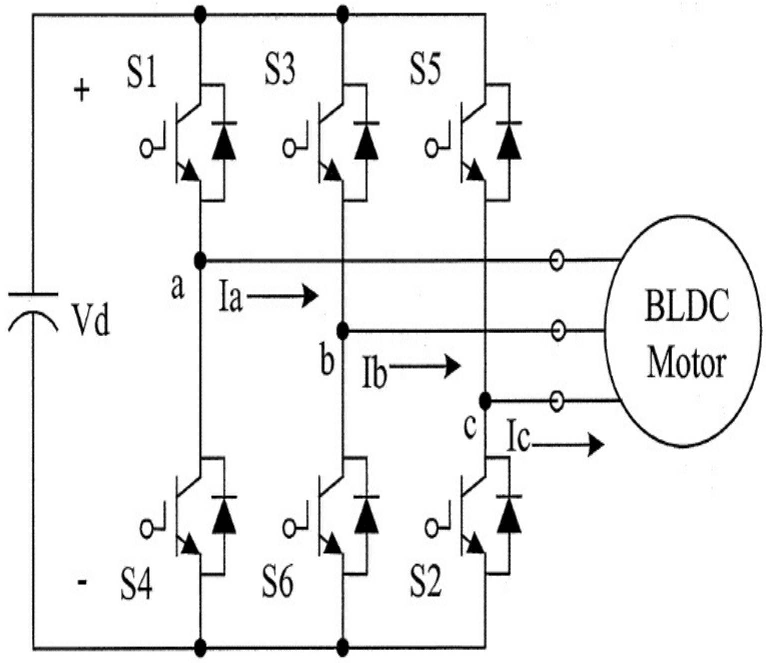

Fig.1 Conventional six-switch three-phase BLDC motor drive systems.

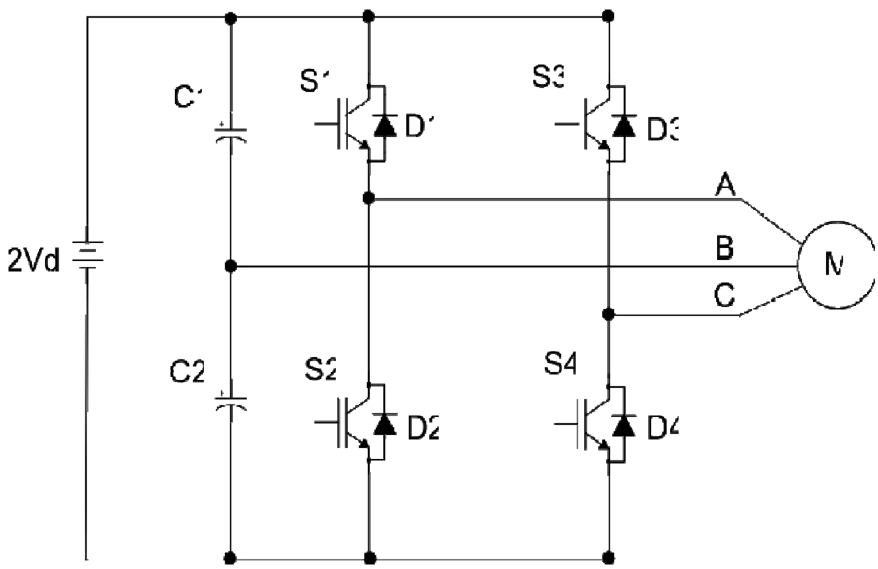

Fig.2 Four-switch converter topology for three-phase BLDC motor.

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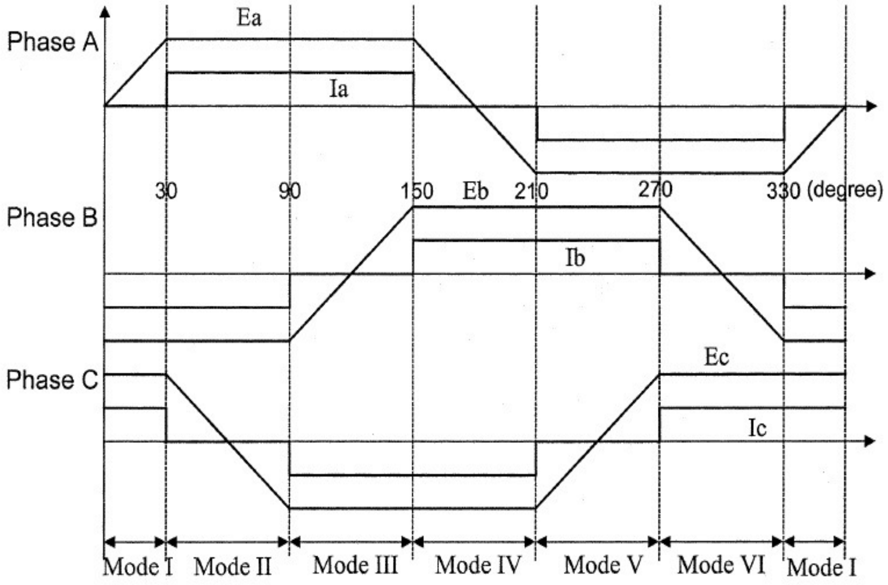

Fig. 3 Desired Waveforms of Three Phase BLDC Motor

In the case of the BLDC motor drive, for every mode one phase current will be zero. Switching sequence of the four switch converter is shown in Table I. According to the operating modes, one can derive the current equations as shown in Table II.

TABLE I. Switching sequences of the four switch converter

Modes	Active Phases	Silent Phases	Switching Devices
Mode I	Phase B and C	Phase A	S4
Mode II	Phase A and B	Phase C	S1 and S4
Mode III	Phase A and C	Phase B	S1
Mode IV	Phase B and C	Phase A	S3
Mode V	Phase A and B	Phase C	S2 and S3
Mode VI	Phase A and C	Phase B	S2

TABLE II. Detailed current equations according to the operating modes

Operating Modes	Current Equations
Mode I ($0^0 < \theta < 30^0$)	$I_b + I_c = 0$ and $I_a = 0$
Mode II ($30^0 < \theta < 90^0$)	$I_a + I_b = 0$ and $I_c = 0$
Mode III ($90^0 < \theta < 150^0$)	$I_a + I_c = 0$ and $I_b = 0$
Mode IV ($150^0 < \theta < 210^0$)	$I_b + I_c = 0$ and $I_a = 0$
Mode V ($210^0 < \theta < 270^0$)	$I_a + I_b = 0$ and $I_c = 0$
Mode VI ($270^0 < \theta < 330^0$)	$I_a + I_c = 0$ and $I_b = 0$

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A. CURRENT REGULATION

Based on the switching sequences in Table 1, the current regulation is actually performed by using hysteresis current control. The purpose of regulation is to shape quasi-square waveform with acceptable switching (ripple) band. Using mode II, the current regulation can be explained as follows: In mode II, I_a and I_b currents ($I_a > 0$, $I_b < 0$) flow and I_c is zero. Therefore, mode II is divided into two cases, such as ___ < and ___ < ,—— > . In this Mode, switches S_1 and S_4 are used. Until I_a (I_b) reaches the upper (lower) limit, S_1 and S_4 are turned on for supplying dc-link energy to increase the current. When the current reaches to the upper limit, S_1 and S_4 are turned off to decrease the current through the anti-parallel diodes D_2 and D_3. At that time, the reverse bias (negative dc-link voltage) is applied to the phases, resulting in decreasing the current [1].

B. BACK EMF COMPENSATED PWM CONTROL STRATEGY

Special attention should be paid to mode II and mode V. In these modes, phases A and B are conducting the current and phase C is regarded as being unexcited, so that it is expected that there is no current in the phase C. However, the back EMF of phase C can cause an additional and unexpected current, resulting in current distortion in the phases A and B. Therefore, in the direct current controlled PWM, the back-EMF compensation problem should be considered. As an example of mode II, in the ideal case, only one current (phase A or phase B) needs to be sensed and switching signals of S_1 and S_4 are identical. In the case of sensing phase A current, the switching signal of S_1 is determined independently and S_4 depends on the S_1 signal, so that phase A current can be regarded as a constant current source. However, in this case, phase B current can be distorted by the phase C current. On the other hand, if phase B is controlled, phase B current can be a constant current source, and then the phase A current can be distorted. The same explanation can be applied to mode V. If phases A and B are regarded as independent current sources, the influence of the back-emf of phase C can be blocked and cannot act as a current source, so that there is no current in phase C. It means that in the direct current controlled PWM, phase A and phase B currents should be sensed and controlled independently and the switching signals of S_1 (S_3) and S_4 (S_3) should be created independently, as shown in Fig. 4 [1].

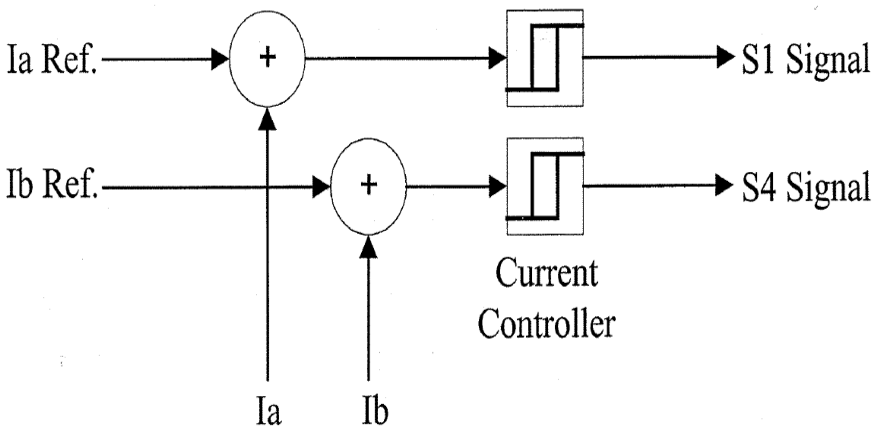

Fig. 4. PWM strategy for compensating the back-emf problem.

C. LIMITATION OF FOUR SWITCH THREE PHASE TOPOLOGY

The overall operating modes of the four-switch BLDC drive are divided into six modes. According to the voltage utilization, these modes are classified into two groups: one is full dc-link voltage utilization (modes II and V) and other is half dc-link voltage (modes I, III, IV, and VI). This irregular voltage utilization distinguishes the four-switch

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converter from the six-switch one in terms of current dynamics, slow , and speed limitation: During the half dc-link voltage period, the motor phases are energized by half value (V_d) of the full dc-link voltage (2 V_d), so that it produces the slower. Therefore, in a PWM period, the rate of current incensement is less than the full dc-link voltage period. This irregular current shape can cause torque ripple, but it can be controllable by adjusting hysteresis band size and fundamentally do not affect any changes in the operation of the BLDC motor drive, such as low speed and four quadrant operations [1].
The other affect of the irregular voltage utilization is speed limitation. In case of the conventional six-switch converter, all motor phases are excited by the full dc voltage. However, in case of the four-switch converter, mainly only half dc voltage is utilized through all operations. This voltage utilization makes the four-switch BLDC motor drive have speed limitation [1].
The speed limitation problem can be overcome by using in conjugation voltage-doublers in conjugation with the four switch converter. Using the half-bridge configuration of diode rectifier, one can obtain double value of the dc voltage from the same ac source. Also if the front-end is replaced with active power semiconductor switches, the dc-link voltage can be controlled to the desired value. The half-bridge diode rectifier can be a low cost and effective solution; otherwise the active voltage-doubler has additional advantage, such as unity power factor correction [1].
The problem with half-bridge diode voltage-doubler is that the efficiency is very low and capacitance value should be very high for ripple free operation. Active voltage-doubler uses two switches extra and the capacitance value is also high. In this paper a novel two input dc-dc boost regulator is used at the front end of four switch converter. The voltage output of regulator is changed according to the rotor speed of BLDC motor by changing the duty ratio. So the motor can run up to the rated speed.

D. TWO INPUT DC-DC BOOST CONVERTER

Two input dc-dc boost converter interfaces one unidirectional input power port and a bidirectional port for a storage element in a unified structure [2]. The structure of the proposed two-input dc–dc boost converter is represented in Fig. 5. As seen from the figure, the converter interfaces one input power source V and a battery (Vb) as the storage element. The proposed converter is suitable alternative for hybrid power systems of PV and Fuel Cell. Three power switches S1, S2 and S3 in the converter structure are the main controllable elements that control the power flow of the hybrid power system. The circuit topology enables the switches to be independently controlled through three independent duty ratios d1, d2 and d3 respectively. As like as the conventional boost converters, diode D5 conduct in complementary manner with other power switches in corresponding modes.

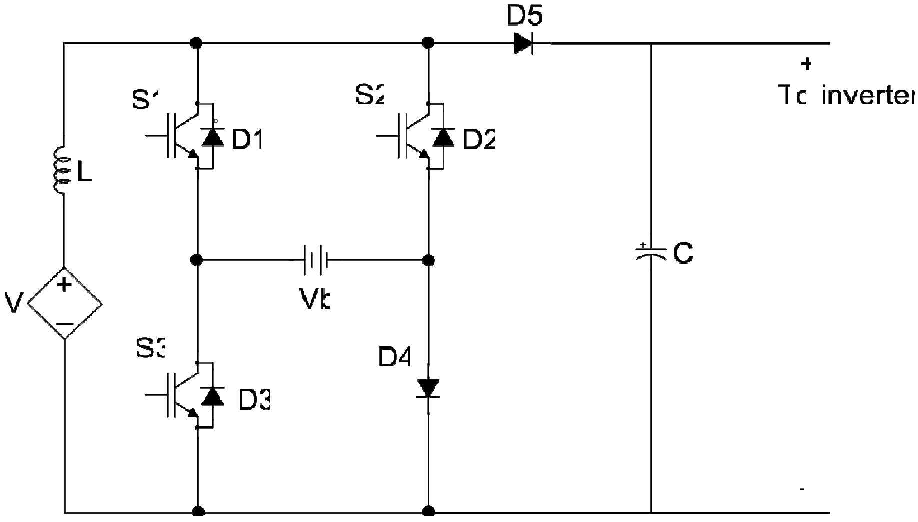

Fig. 5. Circuit topology of the proposed system

Entire operation can be divided in to three operating modes. In mode A, PV source alone drives the inverter, battery is neither charged or nor discharged. In mode B, PV source and battery are combined to give the power to the

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inverter, thereby discharging the battery. In mode C, PV source supplies the power to the inverter along with charging the battery.**3.1.2 Mode B**

In this operation mode, input power source V along with the battery are responsible for supplying the load. Discharging of the battery should be controlled, so for a time 0 to d_1T inductor is charged with $V+V_b$ by discharging the battery and for a time d_1T to d_2T inductor is charged with V. All switches are turned off to discharge the inductor.

Switching state 1 ($0 < t < d_1T$)

At t = 0 S_2 and S_3 are turned on and inductor L is charged with voltage across $V + V_b$.

Switching state 2 ($d_1T < t < T$)

At t = d_1T, switch S_2 is turned off and S_1 is turned ON and inductor L is charged with voltage across V.

Switching state 3 ($d_2T < t < T$)

At t = d_2T, S_1 and S_3 are turned OFF and inductor L is discharged with voltage across $V – V_o$ into the output load and the capacitor through D_5.

By applying voltage – second balance theory to the converter, following equations are obtained,

Therefore, in order to acquire a desired maximum discharging power of the battery, the duty ratio d_1 can be adjusted. By comparing equation 2 and 5, it is evident that for the same discharging period of inductor L mode B can achieve higher output voltage (v_o).

3.1.3 Mode C

In this operation mode, input power source V are responsible for applying the load while the battery charging performance is accomplished. Charging of the battery should be controlled, so for a time 0 to d_1T inductor is charged with $V-V_b$ by charging the battery and for a time d_1T to d_2T inductor is charged with V. All switches are turned off to discharge the inductor.

Switching state 1 ($0 < t < d_1T$)

At t = 0 S_1 is turned on and inductor L is charged with voltage across $V - V_b$.

Switching state 2 ($d_1T < t < T$)

At t = d_1T, switch S_3 is turned on and inductor L is charged with voltage across V.

Switching state 3 ($d_2T < t < T$)

At t = d_2T, S_1 and S_3 are turned OFF and inductor L is discharged with voltage across $V – V_o$ into the output load and the capacitor through D_5.

Therefore, in order to acquire a desired maximum charging power of the battery, the duty ratio d_1 can be adjusted. By comparing equation 2 and 9, it is evident that for the same discharging period of inductor L mode C can only deliver low output voltage level, when comparing with Mode A.

IV. TWO INPUT DC-DC BOOST CONVERTER FED FOUR SWITCH THREE PHASE BLDC DRIVE

In this proposed system two input DC-DC converter is added in the front end of four switch three phase BLDC motor. This novel arrangement is well suited for hybrid vehicles which depend on PV source and battery for power.

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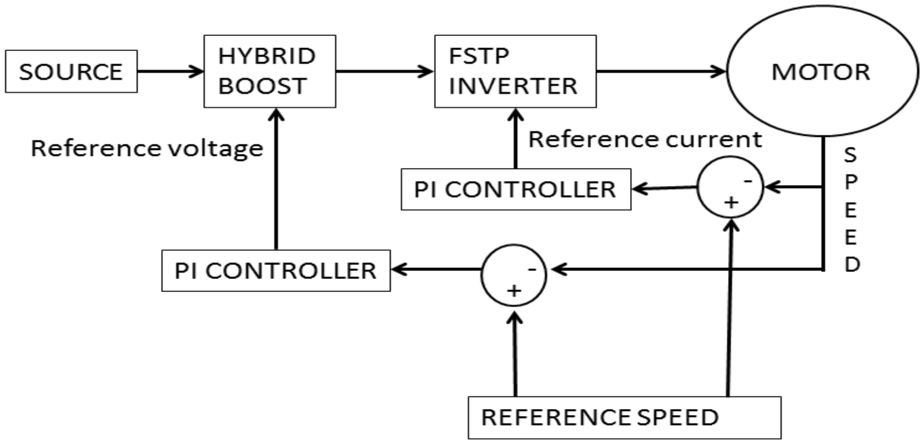

Fig. 6.Block diagram of the two input dc-dc converter fed four switch three phase BLDC drive.

A. VOLTAGE REGULATION OF BLDC MOTOR

The limitation of four switch three phase BLDC drive topology is that it can't run up to rated speed because of its irregular voltage utilisation. In order to solve this problem, a closed loop sub-system is used to regulate the input voltage of BLDC motor.

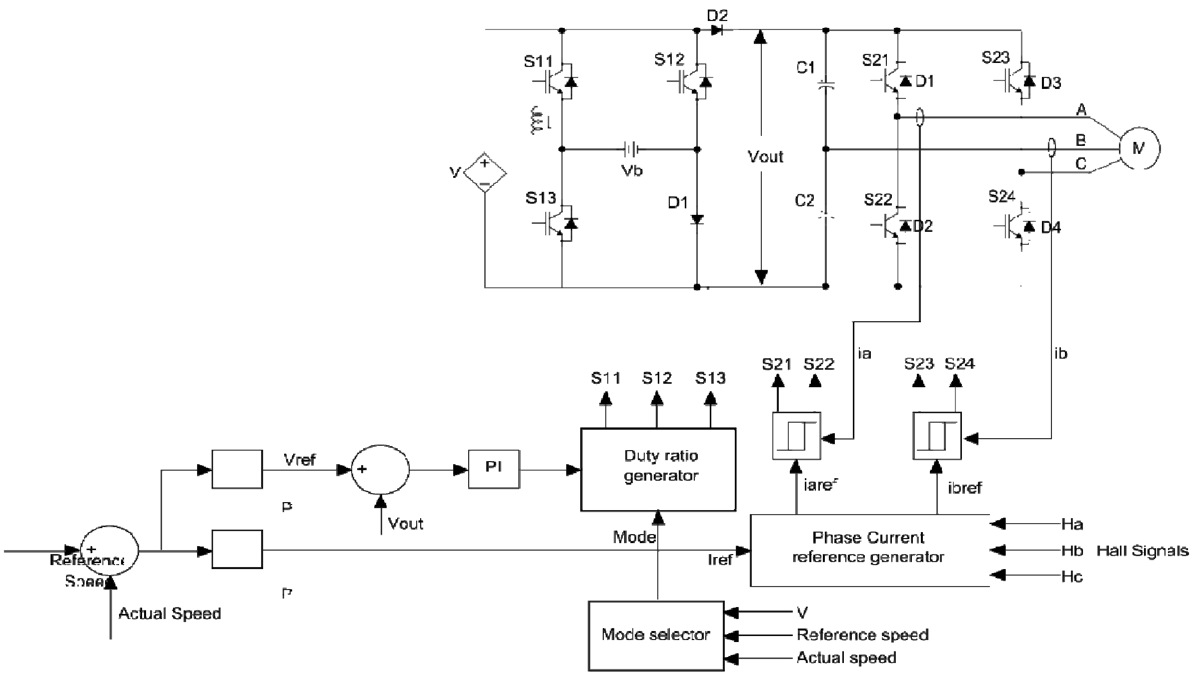

Fig. 7

PI controller is used in the closed loop system; the input of the PI controller is the difference between reference speed and actual speed. The output of PI controller is the reference voltage level and it is given as the input of the two- input

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(hybrid) boost regulator as shown in the Fig. 6. The PI controller can be designed using simulation of six-switch

topology. As explained in the previous chapters, there are three modes of operation for hybrid boost regulator. Different modes are selected according to the speed and voltage output of PV panel. If the speed is less than 90% of reference speed Mode 3 is active, that is PV panel and battery combination supplies the power. If the PV panel voltage is in between 50% to 80% of rated panel voltage, PV panel alone supplies the power where battery neither charges nor discharges. For the remaining cases, battery charges along with boost operation. These modes of operation are done under closed loop condition using PI controller. The input of the PI controller is the difference between reference voltage and output voltage of hybrid boost regulator. By comparing PI controller output with a saw tooth wave, duty ratio of switches of boost regulator is controlled. The circuit diagram of the complete system is shown below (Fig. 7).

V. SIMULATION RESULTS

The simulation is performed in the MATLAB/Simulink R2012a software environment. The main circuit is constructed by building blocks from the Sim-Power Systems library. Voltages and currents are measured using respective measuring blocks and output is connected to scope. Mode selection and switching signals for four switch three phase BLDC motor are generated using M-code. Details of each block are explained in next chapters.
The main circuit simulation parameters of PV panel and BLDC motors are shown in Table III and Table IV respectively.

Table III. Simulation Parameter of PV Panel

Parameter	Value
Short-circuit current, Isc	4.75 A
Open-circuit voltage, Voc	0.6 V
Quality factor, N	1.6
Series resistance	5.1 ∗ 10 ¨ ohm
Energy gap, EG	1.11 eV

TABLE IV. Simulation parameter of BLDC motor

Parameter	Value
Rated voltage	24 V
Maximum current	10 A
Stator phase resistance	0.36 Ω
Stator phase inductance	$0.6 * 10^{-3}$ H
Torque constant	0.036 N.m/ A
Inertia	$4.8 * 10^{-6}$ kgm^2

PV-panel and Lead-Acid battery with nominal voltage 12 V and rated capacity 7Ah is used for modelling. Reference voltage is compared with actual voltage output of converter. The error signal ($e_V = V_{reference} - V_{actual}$) is fed to PI controller. The output of PI controller block is fed to saturation block, which limits the value between 0 and 1. The output of saturation block is fed to PWM generator block. It generates switching signal with varying pulse width according to the required voltage output. PWM generator block compares saturation block output with saw-tooth signal with frequency of 10 kHz to generate PWM signals. According to the mode selected, corresponding switches are selected by index vectorblock. In mode 2 and mode 3, battery discharges and charges respectively. So during these modes discharging/charging current of battery should be controlled. During mode 2 ideally S3 and S2 should be turned on during on period. In order to control the discharging current, S3 is turned on only for 10% of the on period, for the remaining duration of on period S1 and S2 is turned on. Similarly, during mode 3 ideally S1 alone should be turned on during on period. In order to control the charging current, S1 alone is turned on for 10% and for the remaining duration S1 with S2 is turned on. The simulation also provides provision to change manually the

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charging/discharging control limit.

Four switch inverter is modelled using MOSFETS. The operating mode of BLDC motor is found from Hall effect decoder. As explained earlier, for every mode corresponding switches are turned on. Using relay block hysteresis control output of phase current a and b are found out. Reference current for hysteresis control is found out by PI controller. The input of PI controller is the difference between reference and actual speed of BLDC motor. Switching is done depending on operating mode of BLDC motor and the hysteresis control output of ia and ib using embedded matlab function block.

A. TWO-INPUT BOOST REGULATOR

The mode selection of two-input boost regulator is depending on PV voltage and speed of motor as explained in previous chapters. Simulated output of speed of motor, mode of operation of two-input boost regulator and PV voltage is shown in Fig. 8. Two-input boost regulator tracks the speed of BLDC motor and PV panel voltage and changes the mode of operation accordingly.

Output voltage of boost regulator depends on the speed of BLDC motor enabling the motor to work up to rated speed. The variation of the output voltage is shown in Fig. 9 (a) and (b).

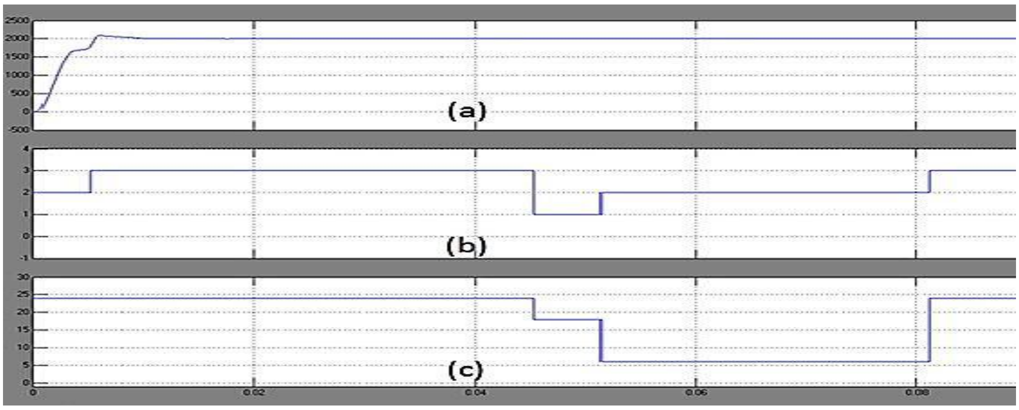
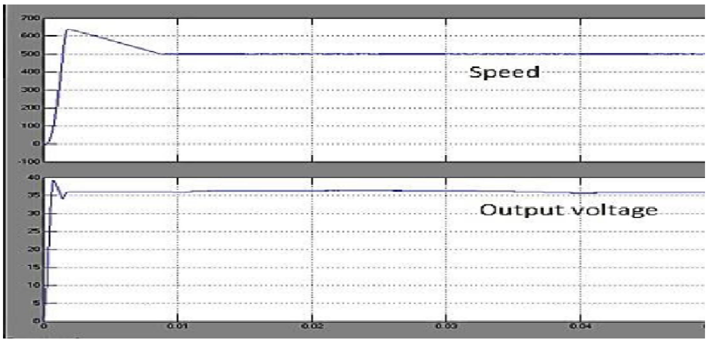


Fig. 8. Mode of operation (a) Speed of motor (b) Mode of operation of two-input boost regulator (c) PV Panel voltage output.



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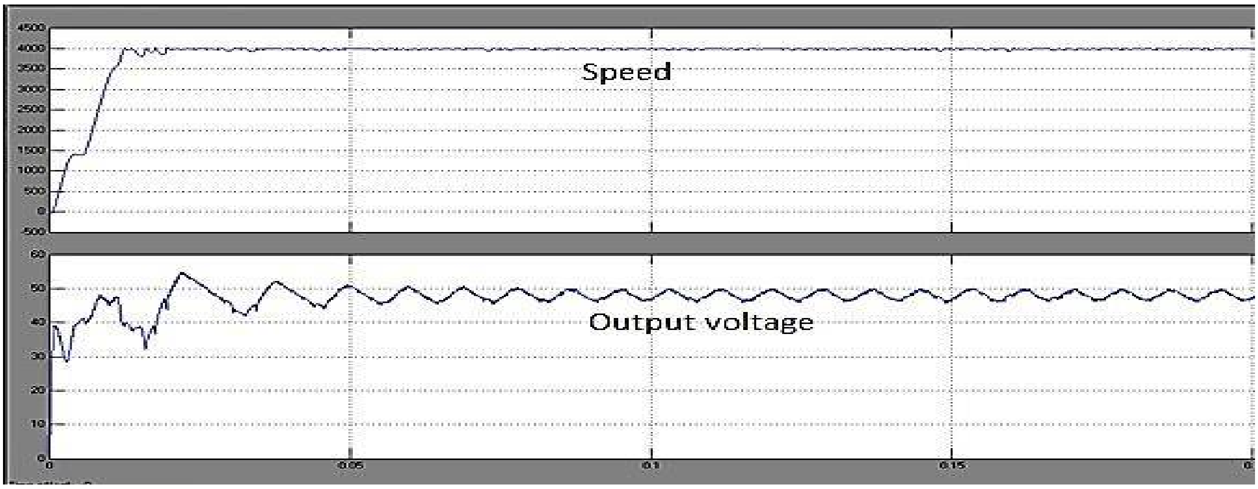

(b)

Fig. 9 Output voltage of two-input boost regulator (a) reference speed = 500 rpm (b) reference speed = 4000 rpm.

For Fig. 9 (a) the reference speed is 500 rpm and output voltage is 36V. For Fig. 8 (b) the reference speed is 4000 rpm and the output voltage becomes 48V.

In Fig. 9 (b) speed of the motor is 4000 rpm which is the rated speed of the motor and the rated voltage is 24V. Two-input boost regulator step-up the voltage to 48V to enable the motor to work up to rated speed.

B. FOUR SWITCH THREE PHASE BLDC MOTOR

Fig. 10 shows the simulated output of current and back emf of the BLDC motor with back emf compensation. Simulation output of close loop speed control is shown in Fig. 11. At 0.5th second the reference speed is changed from -

100 to +100rpm and at 0.3th second torque input is changed from 0.5 Nm to 1Nm. The motor output follows the input conditions correctly.

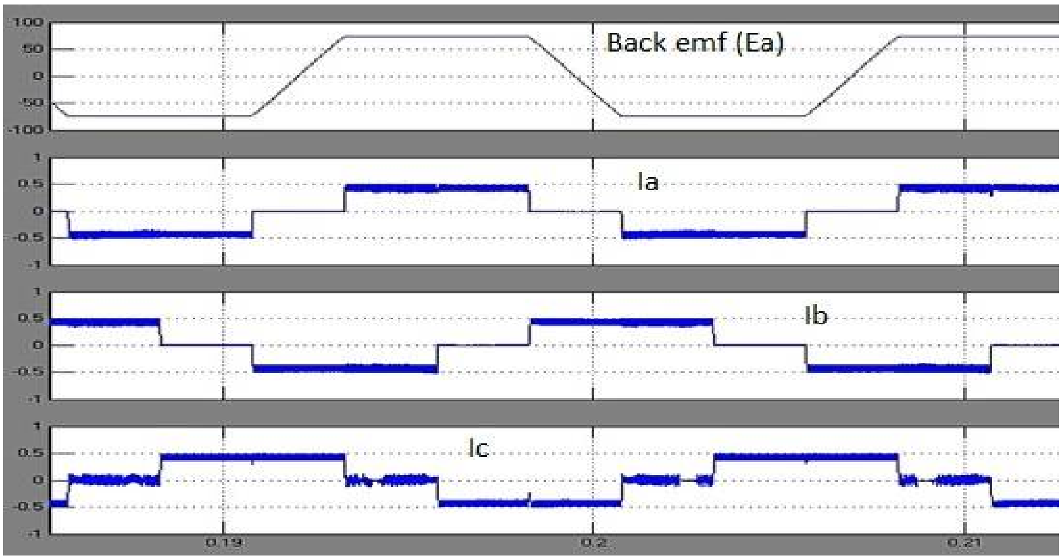

Fig. 10 Back emf of phase A and phase currents of BLDC motor

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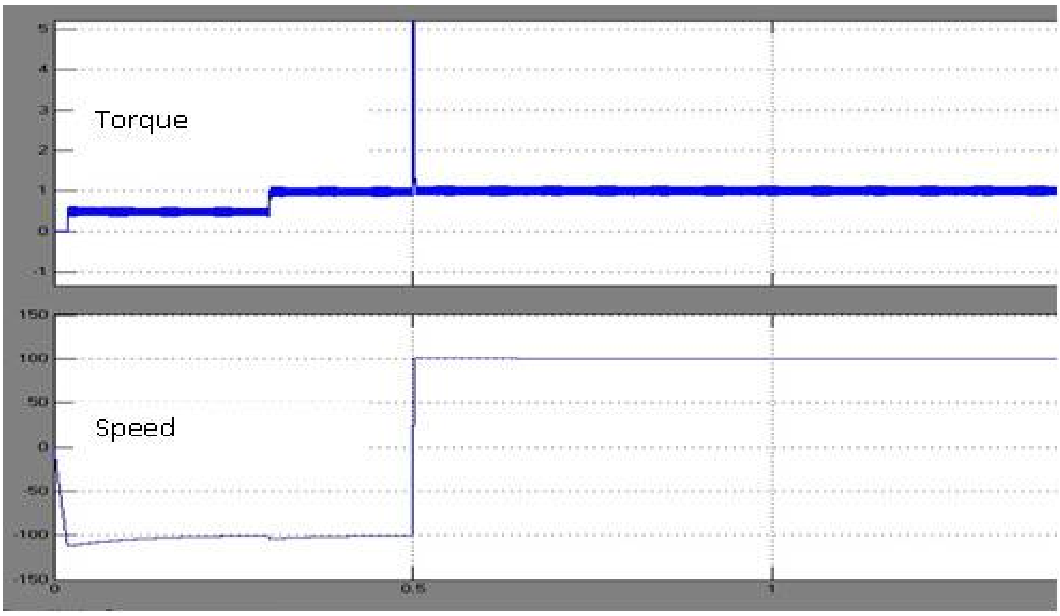

Fig. 11 Close loop operation

VI. CONCLUSION

In this paper, a two-input boost regulator fed four switch three phase BLDC Motor is designed and simulated. The overall circuit design allows elimination of two switches, while maintaining the desired output which helps to reduce the cost of the system. Speed limiting problem of four switch three phase BLDC drive is rectified by the addition of two- input boost regulator. Two-input boost regulator depend on more than one power input (PV cell and battery), hence the proposed system is well suited for low cost hybrid electric vehicles.

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