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Modeling of DC-DC Converter for Solar based Electric Vehicle

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Abstract

Now a days we are looking for alternate sources like electric vehicles, in order to cut down the pollution from automobiles which are growing rapidly. In electric vehicles, A DC-DC converter is used to boost the voltage from solar photo voltaic (PV) array and isolated bidirectional DC-DC converter (IBDC) is used to charge and discharge the battery. In this paper, the proposed use of quadratic double boost converter (QBC) in place of DC-DC converter, which has very high gain when compared with conventional converter. In isolated bidirectional DC-DC converter, soft switching is provided for reduce the switching losses and stresses on switches. The proposed two DC-DC converters are modeled and simulated using MATLAB Simulink and results are shown in this paper.

***Key terms**: Isolated Bidirectional DC-DC converter, Induction motor, Quadratic Double Boost converter, soft switching.*

1. Introduction

Petroleum and oil resources across the world are depleting at a high rate due to large dependency on it, as it is a primary fuel for the automobiles. Releasing of greenhouse gases is affecting the environment. To reduce the pollution and to conserve petroleum products, we are looking for alternate methods like electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs). Presently the research is going on DC-DC converter for electric vehicles [1] and hybrid electric vehicles applications.

Basically two types of DC-DC converters are used in electric vehicles for power electronics interfacing. The two DC-DC converters used in this scheme are unidirectional converter (UQDC) and bidirectional DC-DC converter (BDC). The bidirectional converter used to interfaces the low voltage battery and high voltage DC bus, which are isolated and non-isolated. The different converter topologies for isolated bidirectional DC-DC converters are studied in literature [2] and [3].

Fig. 3 shows the isolated bidirectional DC-DC converter circuit [4], which consists of a high frequency transformer, is used to provide the galvanic isolation between the LV and HVDC buses and L_s is the instantaneous energy storage element. The HF transformer has low volume, less weight and low cost compared to line transformer. The average output voltage and power transfer controlled by phase shift angle. The different phase shift control methods are available, simple phase shift control is used widely for IBDC because of its simplicity. It allows power flow in both the directions from battery to DC link and vice versa. This is used as battery charger (or) discharger. The zero voltage switching (ZVS) and zero current switching (ZCS) can be achieved by soft switching. We can get the soft switching by external snubber capacitor or parasitic capacitor [3], [5].

The quadratic double boost DC-DC converter [6] is used in place of solar based DC-DC converter [7]. The renewable sources like photovoltaic (PV) system and fuel cells have low output voltage. When these are connected to high voltage DC bus which requires large boosting. The quadratic boost converter has high gain compared to conventional boost converter. In this the bidirectional DC-DC converter and quadratic boost converter are used to increasing the voltage level to feed the motor through inverter for propulsion.

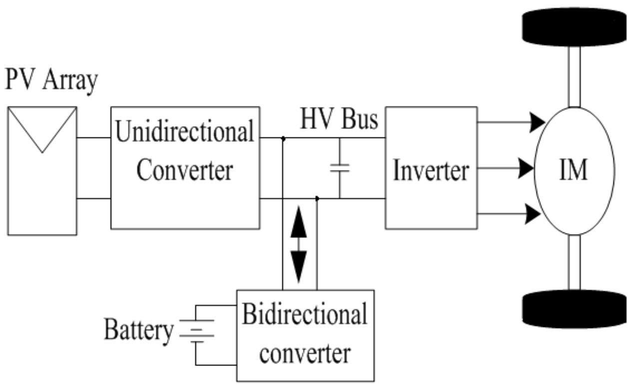


Fig.1. Functional diagram of EV

Different types of motors can be used in electric vehicles (EVs). The 3-ϕ AC induction motor(IM) is commonly used, which has less maintenance, less cost, rugged construction, easy to control and high efficiency under loaded conditions. Three phase inverter with 180 degrees conduction mode is used to convert the high DC bus voltage to AC. Three phase induction motor fed by the Inverter for propulsion.

2. Bidirectional DC-DC Converter

An isolated bidirectional DC-DC converter (IBDC) are widely used in electric vehicle application. The bidirectional DC-DC converter are used where the battery charging and discharging and regenerative braking are required and which is used to connect the low voltage battery (12/24/48 V) to high voltage DC bus systems (200-900V). It allows the power in both the directions from source to load and vice versa. The different IBDC topologies are studied in literature [2].

The basic structure is given below in figure 2,

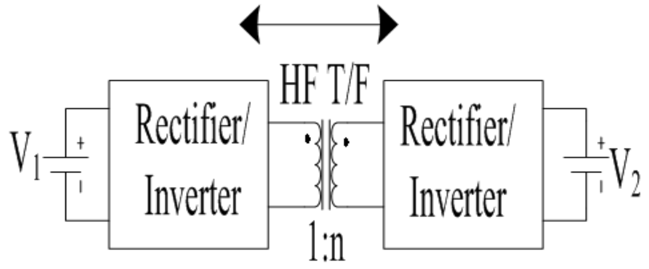


Fig.2. Basic structure of BDC

The Bidirectional converter is used to convert unregulated DC input to high regulated DC output with high voltage gain. Basically, the BDC are used in electric vehicle for battery charging and discharging.

Fig.3 shows the soft switching scheme of IBDC. High frequency square wave voltage is generated at transformer terminals by controlling each bridge.

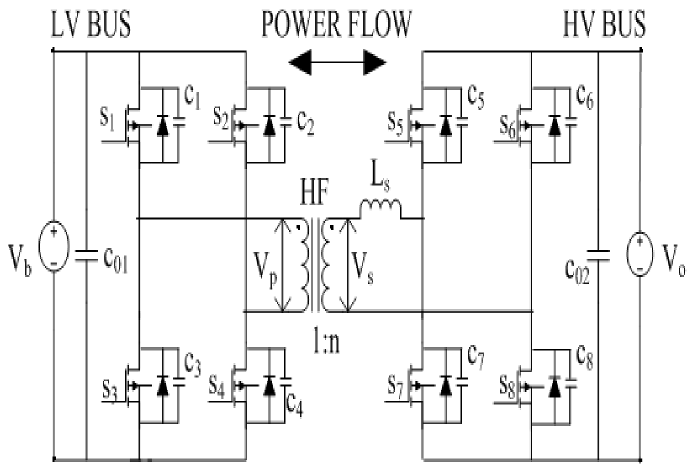


Fig.3. Soft switching Dual active Isolated Bidirectional full bridge converter

The primary side of high frequency transformer is connected to low voltage battery and secondary side of transformer is connected to HVDC bus. Based on the operating voltage of the load, the turn's ratio of the high frequency transformer is determined. By using parasitic capacitor across the each switch we can get the soft switching for proposed topology. Which is reduced the switching losses, stress on switch.

The isolated bidirectional DC-DC converter (IBDC) basically operates in two modes such as,

A. Boost mode:

In this mode, the converter is step up the low voltage to high voltage from battery to load. The operating states of IBDC in boost mode are described below.

State (1): (t_o-t1)

The switches (S_1, S_4) and (S_5, S_8) of the primary and secondary side are turned on respectively at same instant. The positive square wave voltage appears across the transformer primary and secondary. The positive secondary current will flows to load through S_5 and S_8 At the end of this state the series inductor current reaches to zero.

State (2): (t_1-t_2)

The switches (S_2, S_3) and (S_6, S_7) of the primary and secondary side are turned on respectively at same instant. The negative secondary current will flows through S_6 and S_7 to load.

The equivalent circuits for above two states in boost mode is given below.

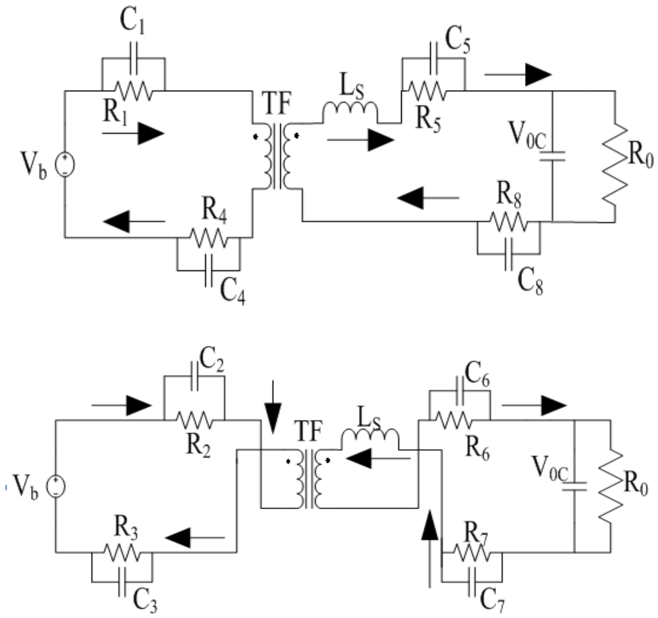


Fig.4. Two operating states of IBDC in boost mode

B. Buck mode:

In this mode, the voltage is step down and current flows from load side to energy storage device (battery) side then battery get charged. In this, the right side bridge acts as inverter and left side bridge acts as rectifier. The converter operates in two states of operation similar to boost mode but the difference is power flows from secondary bridge to primary bridge.

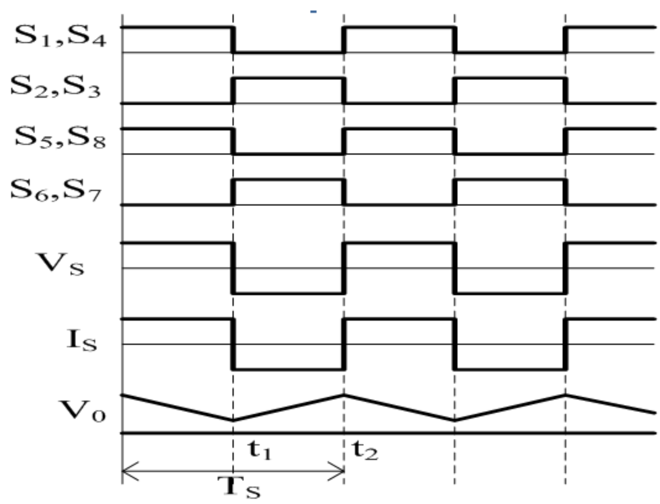


Fig.5. Bidirectional converter model output waveforms

The above figure 5, shows the switching sequence and output waveforms of bidirectional DC-DC converter.

Table1. IBDC specifications:

S. No	Parameters	Value
1	Input voltage	48 V
3	Snubber capacitor	Cs = 33 µF
4	HF T/F Turns ratio	1:n (n=9)
5	Switching frequency (f_s)	20 KHZ

3. Quadratic Double Boost Converter with Solar Input

A. Characteristics of PV Array:

The PV cell characteristics are modelled by using single diode equivalent circuit [6]. The PV cell mathematical model can be developed in MATLAB Simulink.

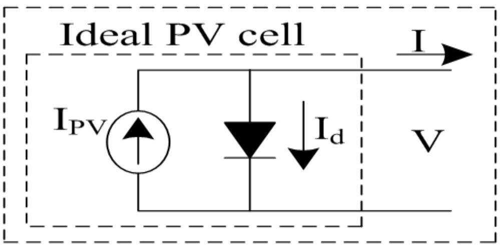


Fig.6. PV cell equivalent circuit

From the above figure, the basic equations of ideal PV cell can be written as,

$$I = I_{PVcell} - I_d \quad (1)$$

$$I_d = I_{0cell}[\exp(qv/\alpha KT)-1] \quad (2)$$

From equations 1 and 2 we get,

$$I = I_{PVcell} - I_{ocell}\left[\exp\left(\frac{qV}{\alpha KT}\right)-1\right] \quad (3)$$

Where,

'I_{PVcell}' is a current generated by the incident light, Id is the diode current equation, 'q' is represented as electron charge [1.6217646*10-19C], K is Boltzmann constant [1.3806503*10-23J/K], and T is the temperature.

Practically, the arrays are consisting with number of connected PV cells. If the cells are connected in series voltage is increases and cells are connected in parallel current increases. The equivalent circuit of ideal PV cell with parallel resistance (R_P) and series resistance (R_S) is given below figure. 7.

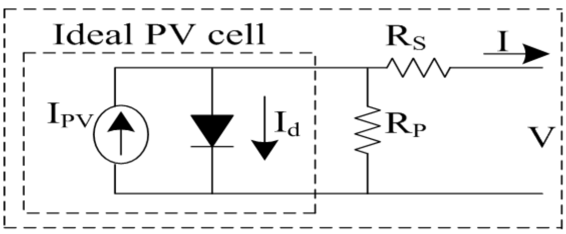


Fig.7. Equivalent circuit of practical PV device

The current equation for above figure can be written as,

$$I = I_{PV} - I_o\left[\exp\left(\frac{V+IR_s}{V_t\alpha}\right)\right] - \left(\frac{V+IR_s}{R_p}\right) \quad (4)$$

Where,

$$V_t = N_{sk}T/q$$

Number of cells is connected in series; the series resistance is very small compared to parallel resistance for good solar cell. Open circuit voltage (V_{OC}), Short circuit current (I_{SC}) and maximum power point (MPP) are the three important parameters of I-V curve is shown in below figure. 8.

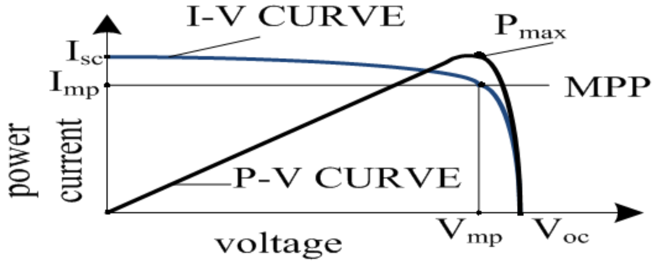


Fig.8. I-V and P-V curves of PV cell

B. Quadratic Double Boost DC-DC Converter:

The output voltage of renewable energy sources like PV arrays, fuel cells have a low output voltage. When these are connected to the high voltage bus (power grid) the output voltage has to be boosted up.

The quadratic double boost converter [6] when compared with conventional boost converter, for the same input voltage and same duty ratio, the output voltage is very high for quadratic boost converter. The solar is considered as the input of the proposed converter shown in below figure. 9.

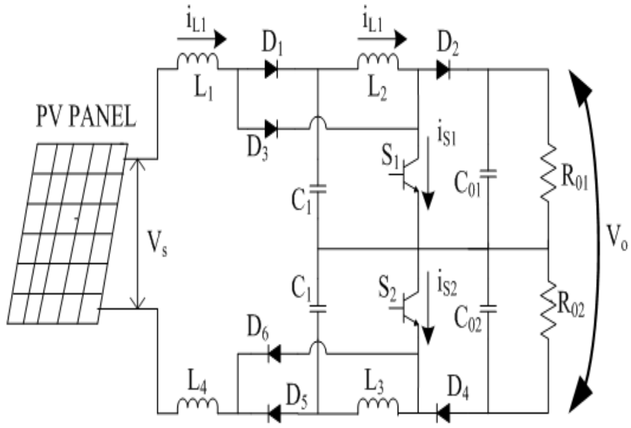


Fig.9. Quadratic double boost converter with solar input.

Analysis of Continuous Conduction Mode:

Stage (1): (t_0-t_1)

The switches S1and S2 are turned on, during this stage, the diodes D_2 and D_4 are not conducted (inversely polarized), and cuts the powers supply to output.

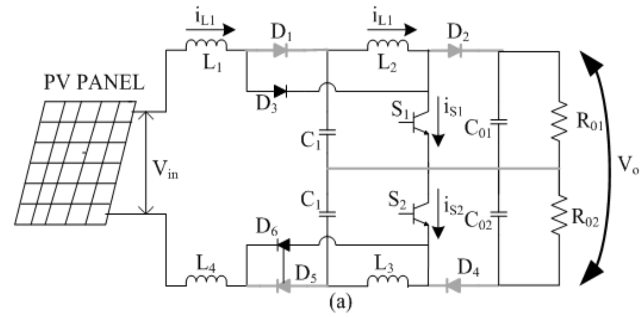
$$i_{S1} = i_{L1} + i_{L2} \text{ and } i_{D1} = 0 \quad (5)$$

Stage (2): (t_1-t_2)

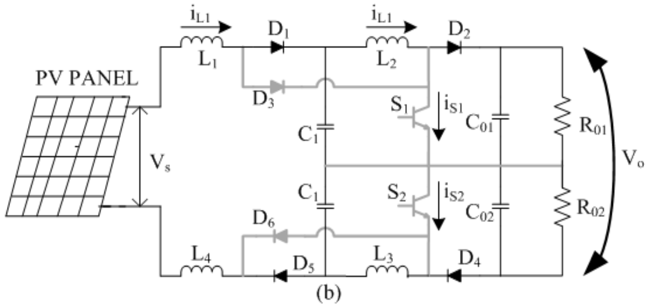
The switches S1 and S2 are turned off, during this stage, the diodes D_1 and D_2 are in forward bias and the active elements L_1

and L_2 will deliver the energy to the output. The currents i_{S1} and i_{S2} are null.

$(i_{S1}=i_{S2}=0)$.



10 (a)



10 (b)

Fig.10. Equivalent circuits for IBDC (a) stage1 (b) stage2

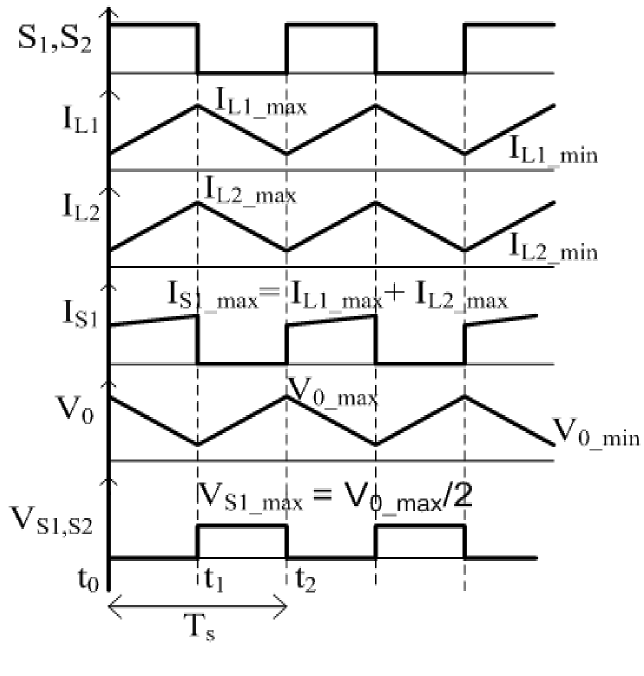


Fig.11. Model output waveforms of proposed converter

The above fig. 11, shows the output waveforms for the operating stages with their respective time intervals corresponding to each stage.

Calculations of Ideal Static Gain:

Consider, the source voltage is V_S, inductor i_{L1} as a constant current source of magnitude i_{L1} and V_{C1} is the middle capacitor voltage.

The energy delivered by the source in the time interval t0-t1,

$$E_{Vin} = V_S.i_{L1}.\Delta t_1 \qquad (6)$$

The energy absorbed by the capacitor C_1 in the time interval t_1-t_2,

$$E_{VC1}=V_{C1}.i_{L1}.\Delta t_1 \qquad (7)$$

Assuming the converter to be an ideal, during the operating period all the energy delivered by the source and observed by the middle capacitor C_1.

By solving the above equations, we obtain the ideal static gain for the first part of the proposed converter.

$$\frac{V_{C1}}{V_S} = \frac{1}{(1-D)} \qquad (8)$$

For the second part of the converter, consider middle capacitor voltage as input for the second part and i_{L2} is constant current source of magnitude i_{L2}. Same analysis is also followed for second part of converter

Using the principle of superposition theorem, the total ideal static gain of the quadratic boost converter is given by,

$$\frac{V_0}{V_S} = \frac{1}{(1-D)^2} \qquad (9)$$

Table.2. QBC specifications:

S.No	Parameters	Value
1	Input voltage (Solar output)	111.1 V
2	Inductance	L1,L4 = 0.5 mH L2,L3 = 2 mH
3	Capacitor	C1,C2 = 330 µF C01,C02 = 330 µF
5	Switching frequency (f_s)	5 KHZ

4. Voltage Source Inverter Fed Three Phase AC Motor

A. Three Phase Voltage Source Inverter:

The following figure 12, Shows the basic conventional three phase voltage source inverter.

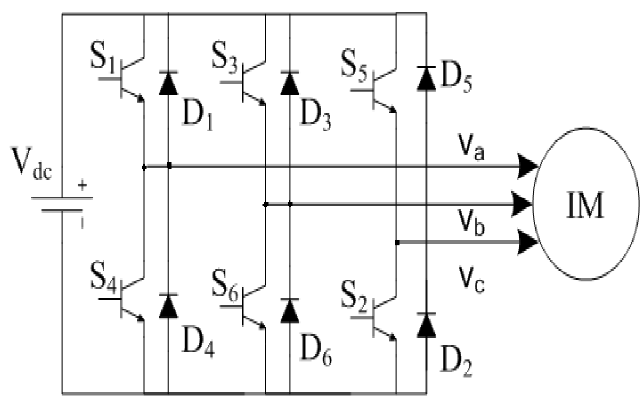


Fig.12. 3-phase VSI

A conventional inverter is used to provide AC voltage to three phase induction motor.

The switching operation of this scheme is shown in below table.1

Table.3. Switching Sequence of VSI

Mode	S_1	S_2	S_3	S_4	S_5	S_6
1^{st}	ON	OFF	OFF	OFF	ON	ON
2^{nd}	ON	ON	OFF	OFF	OFF	ON
3^{rd}	ON	ON	ON	OFF	OFF	OFF
4^{th}	OFF	ON	ON	ON	OFF	OFF
5^{th}	OFF	OFF	ON	ON	ON	OFF
6^{th}	OFF	OFF	OFF	ON	ON	ON

B. Three Phase Induction Motor:

The $3-\emptyset$ induction motor is used in modern electric vehicle widely, because of following advantages like high rated power, easy to design, flexible control and high reliability.

By mathematical modeling of squirrel cage motor we can get the equations from the equivalent circuit.

$$V_{ds} = i_{ds}.R_S + \frac{d\emptyset_{ds}}{dt} - \omega\emptyset_{qs} \quad (10)$$

$$V_{qs} = i_{qs}.R_S + \frac{d\emptyset_{qs}}{dt} + \omega\emptyset_{ds} \quad (11)$$

$$V'_{dr} = i'_{dr}.R'_r + \frac{d\emptyset'_{dr}}{dt} - (\omega - \omega_r)\emptyset'_{qr} \quad (12)$$

$$V'_{qr} = i'_{qr}.R'_r + \frac{d\emptyset'_{qr}}{dt} + (\omega - \omega_r)\emptyset'_{dr} \quad (13)$$

Electromagnetic torque,

$$T_e = 1.5\rho\,(\emptyset_{ds}i_{qs} - \emptyset_{qs}i_{ds}) \quad (14)$$

Where,

V_d is the voltage of d-axis quantity, V_q is the voltage of q-axis, r and s is the rotor and stator quantities, l is the leakage inductance and L_m is the magnetizing inductance.

ω is the reference frame angular velocity and ω_r is the electrical angular velocity.

$$\emptyset_{ds} = i_{ds}.L_s + L_m.i'_{dr} \quad (15)$$

$$\emptyset_{qs} = i_{qs}.L_s + L_m.i'_{qr} \quad (16)$$

$$\emptyset'_{dr} = i'_{dr}.L'_r + L_m.i_{ds} \quad (17)$$

$$\emptyset'_{qr} = i'_{qr}.L'_r + L_m.i_{qs} \quad (18)$$

$$L'_r = L'_{lr} + L_m \quad (19)$$

$$L_S = L_{ls} + L_m \quad (20)$$

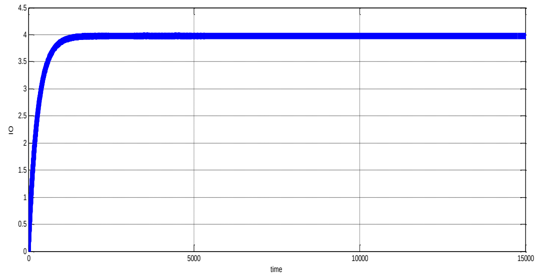
Where,

R_s is the stator resistance, T_m is the shaft mechanical torque and T_e is the electromagnetic torque.

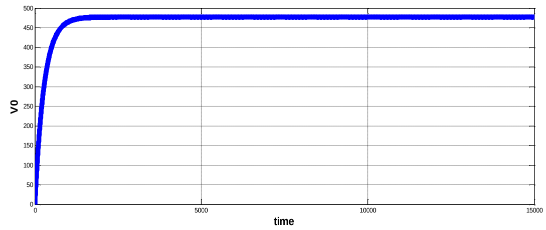
5. Simulation Results and Analysis:

A) Isolated bidirectional converter output waveforms:

Boost mode:



13 (a)



13 (b)

The figure.13 (a) Total output current and (b) output voltage of isolated BDC in boost mode (discharge) with battery input 48V.

Buck mode:

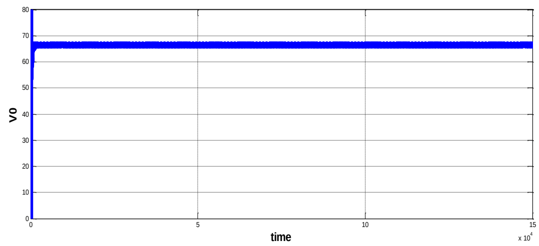
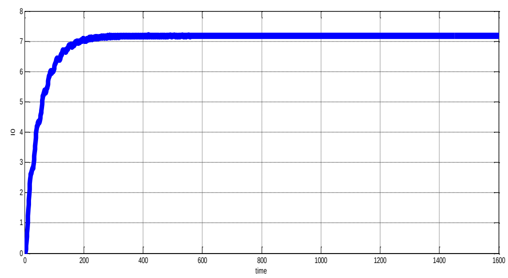
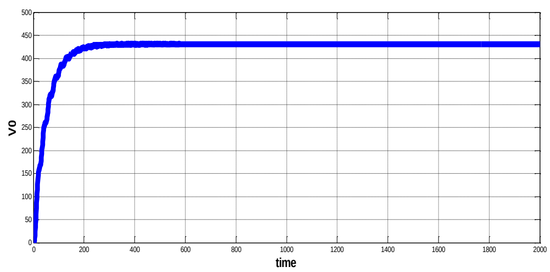


Fig.14. Output voltage of IBDC in buck mode with 400V input.

B) Quadratic boost converter output waveforms:



15(a)



15(b)

Fig.15. (a) Output current (b) output voltage of QBC with solar input of 111.1V

C) Motor waveforms:

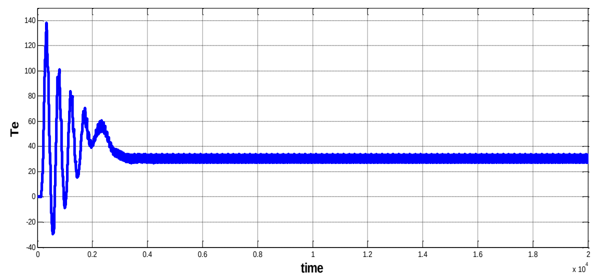


Fig.16. Electromagnetic torque (T_e)

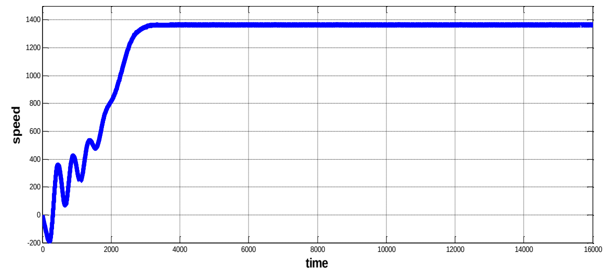


Fig.17. Speed of the motor (rpm)

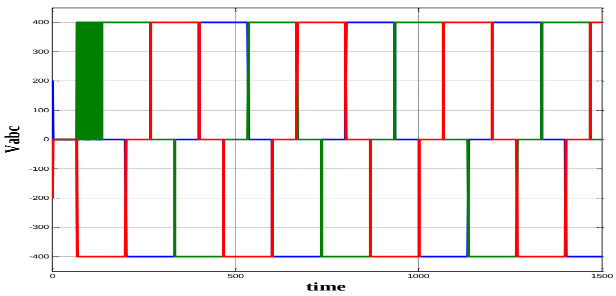


Fig.18. 3−∅ Stator voltages

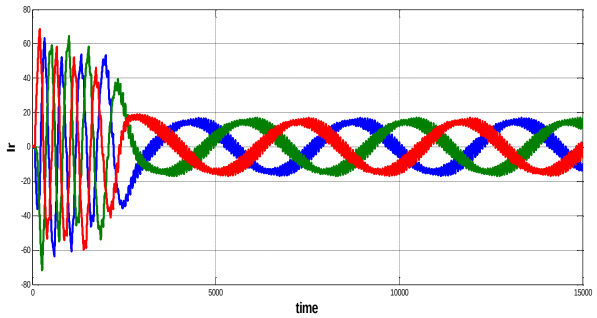


Fig.19. 3-ϕ Stator currents

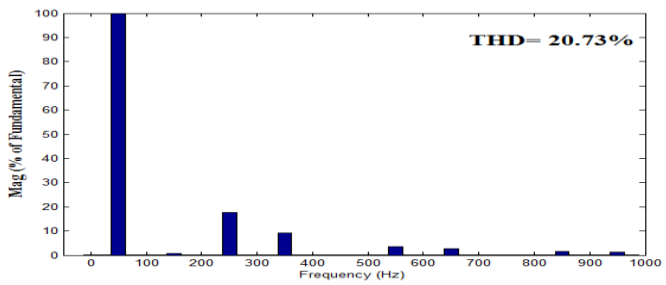


Fig.20. THD of phase current

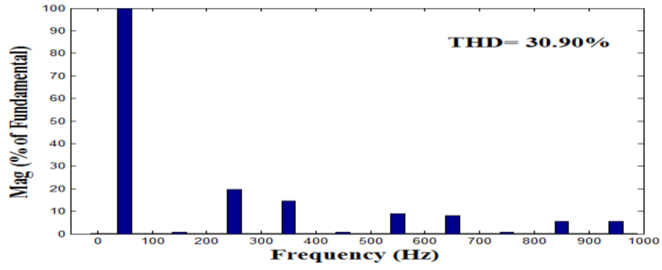


Fig.21. THD of phase voltage

6. Conclusion

In order to provide a constant high voltage to the load (induction motor), the output from PV array is boosted by using quadratic boost converter which have better boosting properties when compared with conventional DC-DC boost converter. In electric vehicle, energy storage is an important aspect; batteries are used widely for energy storage. For charging and discharging of battery isolated bidirectional DC-DC converter is used. In this scheme, soft switching is used to improve the performance of the converter. So, the switching losses and stress on switch are reduced in the process of charging and discharging of battery

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