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Design and analysis of power convertors for electric vehicle applications

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Abstract The surge in the cost of fuels can be accounted as a major trigger which leads to the advent of hybrid vehicles. The hybrid electric vehicles are in the reckoning to address the dangers of the exponential increase in contamination of air and global warming associated with greenhouse gases. A vehicle that is a combination of reversible storage devices like batteries and main energy sources (oil or gas) [1]. A HEV emanates reduced emission from its IC engine when compared to a pure petrol car of the same size. In the context of Hybrid Electric Vehicle, the DC-DC power converters are the electronic devices that condition the source voltage of one level to the output voltage of another level of different DC voltage based on the application provided for the electric vehicle for charging and discharging modes. The need for these power converters arises from the different voltage ratings of the hardware equipment being used. These converters acting importance due to the fact that they are efficient, easy to design and cost effective in the Hybrid electric vehicle application. The paper presents the modelling, design and simulation of buck converter the bidirectional converter based on the transmission line of powertrain of electric vehicle application. The aim is to obtain from a stable input voltage to the output voltage which is lower with high frequency and minimum ripple with specified fixed frequency in the buck operation. In bidirectional converter, the voltage stepdown is required while charging the battery while step up is needed while providing power to the motor from the battery. The design of the above-mentioned converters is performed using the standard method present in the literature. The simulation is done on PowerSim 8.0. The waveforms for the voltage and current for inductor, capacitor and the diode is also obtained. It is found that the simulation results of the voltages are in close agreement with the analytical calculations**.**

Keywords— Power convertors, Electric Powertrain, PowerSim, Buck, Bidirectional, DC-DC convertors

1. Introduction

The surge in the cost of fuels can be accounted as a major trigger which leads to the advent of hybrid vehicles. The hybrid electric vehicles are in the reckoning to address the dangers of the exponential increase in contamination of air and global warming associated with greenhouse gases. A vehicle that is a combination of reversible storage devices like batteries and main energy sources (oil or gas) [1]. A HEV emanates reduced emission from its IC engine when compared to a pure petrol car of the same size. This is because HEVs gasoline engine is smaller than comparably sized pure gasoline burning vehicle [2-3]. The idle emissions are reduced as the IC engine is shut down and restarted only when necessary. The best characteristics of IC engines and electric batteries are utilized as and when

necessary. This results in an enhanced fuel economy, less emissions, optimum power distribution for driving and auxiliary power requirements.
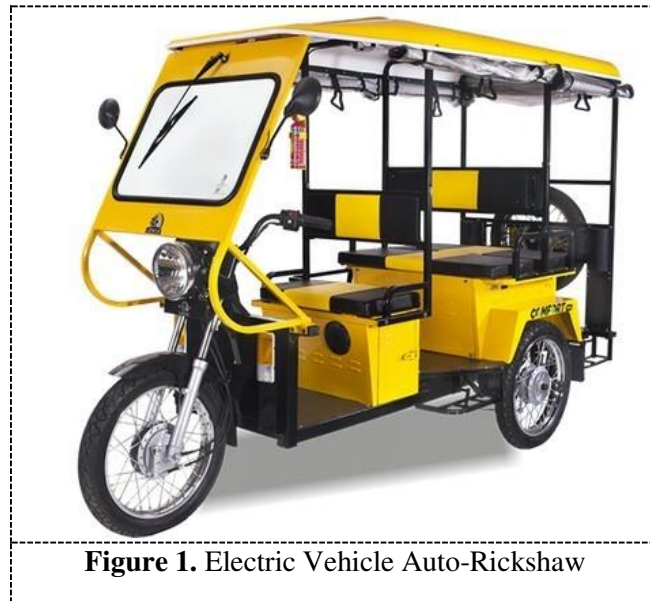

Figure 1. Electric Vehicle Auto-Rickshaw

In the electric power aspect, the design of power electronics converters play a very important role in an efficient conversion of power as per the ratings of the original power source and the ratings of the equipment used. Till recently, the use of power electronics was avoided in the architecture of electric vehicles owing to the huge cost involved. But presently, the power electronics gain immense importance and the reasons are the following. Firstly, the modern architecture which included the integrated switching and fusing functions into a single component with increased reliability. The power convertors can be used for different control methods Secondly, the conversion of power is realized by using adjustable speed drives. Lastly, the conversion of voltage as per the demand of the application can be efficiently realized by using power electronics. The different components used in the power electronics of an electric vehicle are rectifiers, inverters dc-dc converters etc.

The dc-dc power converters are used to condition the level of the voltage and to deliver a stable dc bus voltage. The input DC voltage is converted to a regulated output DC voltage. This process of conversion is highly efficient with an efficiency percentage of almost 90 %.. These converters operate at high frequencies of the order of 10 kHz - 1MHz. The high frequency ensures that size of the hardware components involved in the converter is small which in turn helps in the EV applications. [11]

The various types of types of DC-DC convertors which are not isolated are: Buck converter, Boost converter and Bidirectional converters.

Wangsupphaphol A et al [10] simulated the powertrain for EV using a bidirectional convertor on MATLAB. The result shows the capability to settling supply a significant amount of power for step load change within few milliseconds. The sudden demand for the power from the load can be obtained from the supercapacitor. This process minimizes the battery stress compared to the pure battery supply system. In this work, the buck and bidirectional converter is designed for conditioning the voltage between the power source, battery and motor. Please refer to the below diagram which indicates the power train diagram of "Electric Vehicle.

Figure 2. Power train diagram of Electric Vehicle
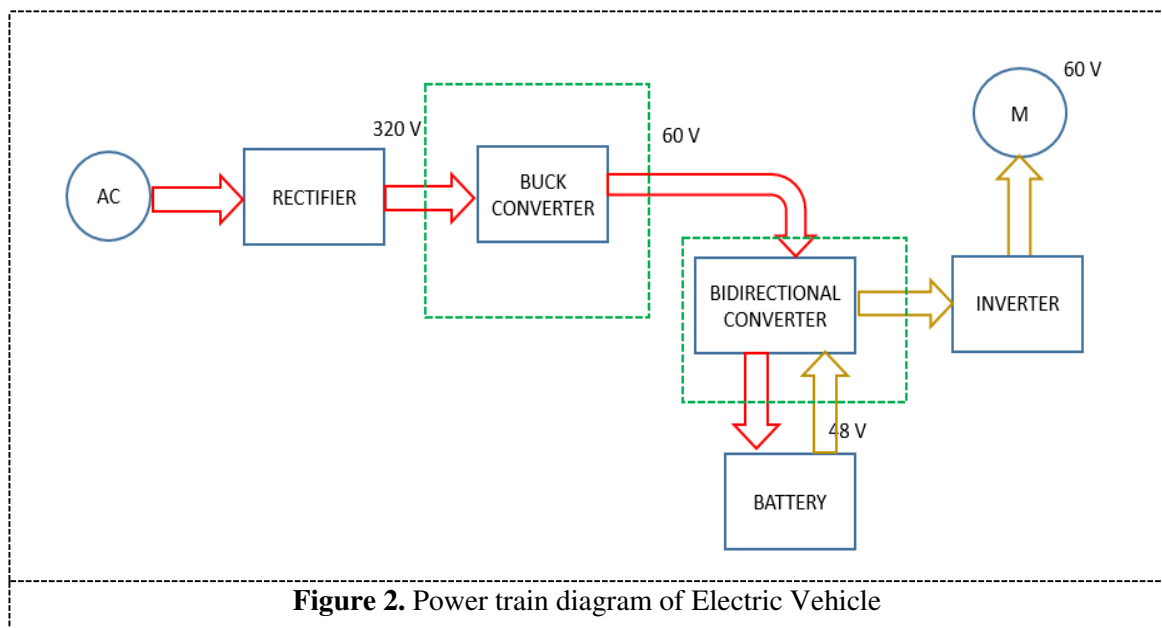
As evident from the above diagram, the source AC voltage (230V) is rectified to DC using a rectifier. The rms value of the rectified DC voltage is320 V (i.e. √2 * 230). This voltage is reduced to 60 V using a buck converter. Further, the 60 V is reduced to 48 V which is the rating of the battery. This is the procedure of the charging the battery. The 48V battery drives the 60 V using the bidirectional converter which now acts like a boost converter. The analytical design is performed using the formulae available in the literature. The simulation is performed on PowerSim software. The results are validated with the analytical design.

2. Analysis and Design
Buck Converter

The buck converter produces a pure DC voltage which is less than the input voltage in magnitude. To accomplish this action, the converter uses a combination of inductor-capacitor (LC) low pass filter. This low-pass filter is assumed to be ideal. The function of the buck converter is to provide an output voltage less than that of input voltage. The values of output current and voltage in the inductor is obtained for the switch open and switch closed states. In the steady state condition, the gross change for the current in the inductor is zero for a period. The average value of the voltage across the inductor is zero.


Figure 3. Simulation of the buck converter in Psim
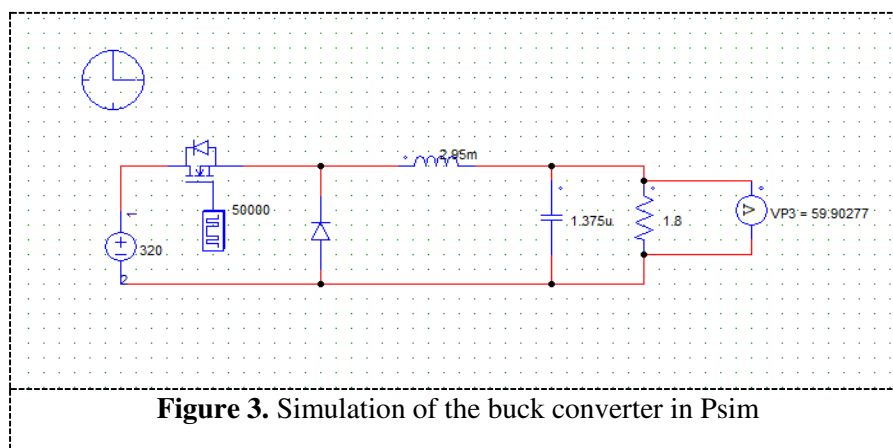
Operation - switch closed

Figure 4. Operation of closed switch buck converter
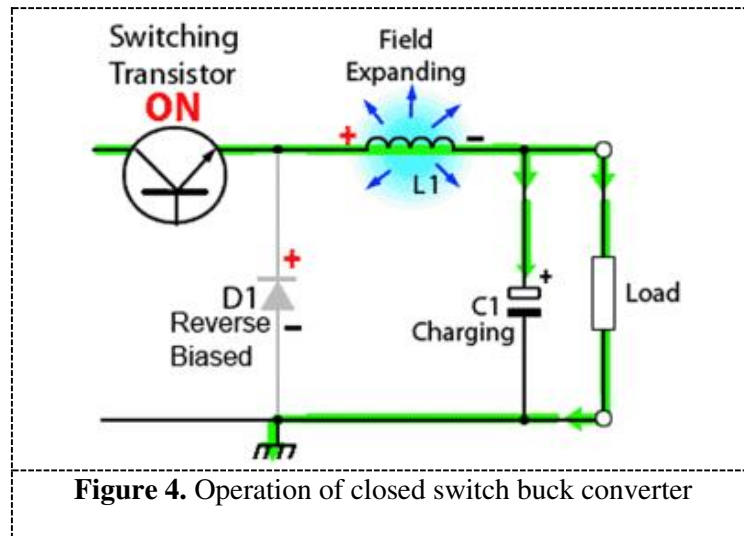
When the switch is closed, the diode does not allow current to pass through it (reverse biased). The magnitude of the voltage in this condition across the inductor is $V_L = V_s - V_o$. As the rate of change of current is positive, the current increase in a linear mode. The net change in current when the switch is closed is obtained as per the below equation.

Note: D is duty cycle

$$(i_L)_{closed} = DT$$

Operation - switch open

Figure 5. Operation of open switch buck converter
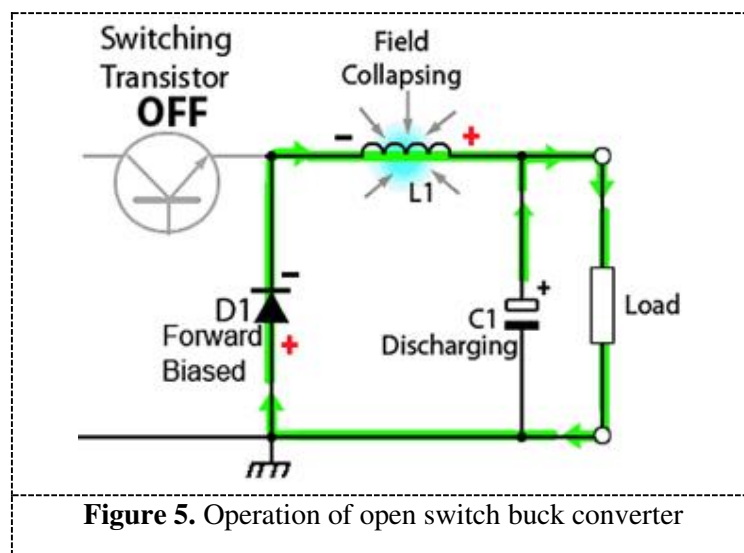
Similarly, in the open state of the switch, the diode allows current to pass through it (forward biased) because the polarity of the inductor changes. The inductor acts like the main source of power to the circuit. The magnitude of the voltage across the inductor in the open state of the switch $V_L = -V_o$.
The rate of change of current in the open state of the switch is negative. Hence the current is observed to decrease in a linear pattern. The difference in the current from the original is as below.

ANALYSIS PART

Buck converter Inputs for

Power = 2kW

Input Voltage V_s = 320V

Output Voltage V_o = 60V

Frequency f = 50kHz

The average Inductor Current and output ripple Voltage is no more than 1%

Diode (D) $= \dfrac{60}{320} = \dfrac{V_o}{V_s}$

$\qquad$ = 0.1875

Power (P) = V_o^2 * R

Resistance (R) = V_o^2 / P

$\qquad$ = 60^2/2000

$\qquad$ = 1.8Ω

Inductor Current   (I_L) = Output Current   (I_o)

$\qquad\qquad$ I = V_o /R

$\qquad\qquad$ = 60^2 /1.8

$\qquad\qquad$ = 33.33A

Average Inductor Current ΔI_L = 1% I_L

$\qquad\qquad\qquad$ = 0.33A

Average Voltage = 1% V_o

$\qquad\qquad$ = 0.6V

Inductor (L) $= \dfrac{(V_s - V_o)D}{\Delta I_L * f}$

$\qquad = \dfrac{(320 - 60)0.1875}{0.33 * 50000}$

$\qquad$ = 2.95 mH

Capacitor (C) $= \dfrac{\Delta I_L}{8 * f * \Delta V}$

$\qquad = \dfrac{0.33}{8 * 50000 * 0.6}$

$\qquad$ = 1.75 μF

Bidirectional Converter

The bidirectional converter consists of two MOSFET switches i.e. the switch1 operates the voltage source to the battery whereas as switch2 operates the motor through the battery. It is known as bidirectional converter. In this operation when the switch1 is turned ON the buck mode will operate and supplies the voltage from source to battery whereas switch2 is turned ON the boost mode will operate and supplies the voltage from battery to the motor to run the wheels by keeping the power as constant throughout the circuit.

Simulation of Powertrain

The DC-DC converters for the electric powertrain are simulated by using one buck converter and one bidirectional converter.

The conditions of the analytical buck converter are shown in the below table.

The values of inductance, capacitance and resistance are calculated using the standard method available in the literature.

Table 1. Analysis calculation values of Buck Converter

PARAMETER	VALUE
INPUT VOLTAGE	320 V
OUTPUT VOLTAGE	60 V
DUTY CYCLE	0.1875
FREQUENCY	50 kHz
INDUCTANCE	2.95 mH
CAPACITANCE	1.75 µF
RESISTANCE	1.8 Ω

The resultant of the voltage obtained from the buck converter is applied to the bidirectional converter which will charge the battery in the buck action. Consequently, the battery powers the motor in the boost action of the bidirectional converter and thereby discharges itself.

BATTERY CHARGING MODE

In the battery charging mode, the bidirectional act as buck operation which is opearted in two modes i.e switch1 is ON mode whereas switch2 is OFF mode. The energy from the primary source of power is stored in the inductor in the form of magnetic field. This cycle repeats when switch2 is ON position.Hence the inductor recieves energy from the primary source when the switch is ON.
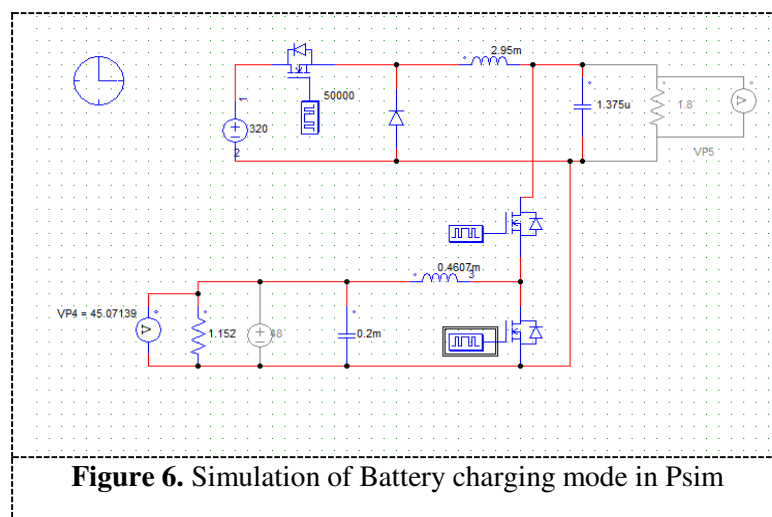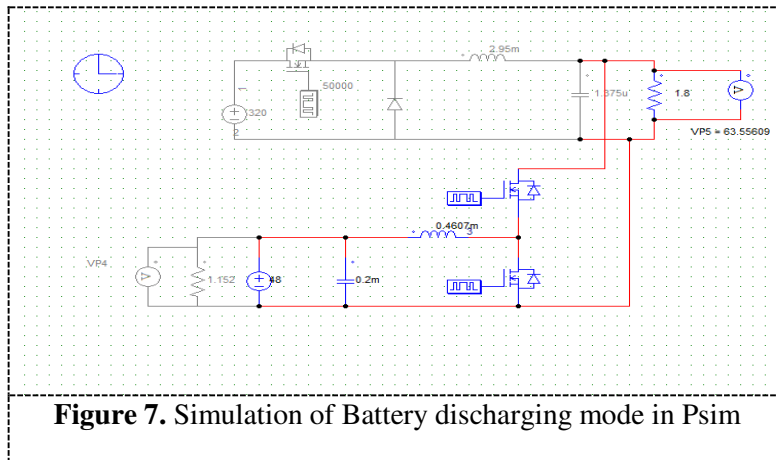

Figure 6. Simulation of Battery charging mode in Psim

The values of inductance, capacitance and resistance are calculated using the standard method available in the literature.

BATTERY DISCHARGE MODE

Figure 7. Simulation of Battery discharging mode in Psim

In this mode, the bidirectional act as boost operation by closing the switch2 and by opening switch1. In this operation the bidirectional will boost up the voltage from battery to the motor to run the wheels. The average current through the inductor in this mode is zero.

Analysis Part

The values of inductance, capacitance and resistance are calculated using the standard method available in the literature.

Bidirectional converter Inputs

Power = 2kW

Buck Voltage V_s = 60V

Battery Voltage V_o = 48V

Frequency f = 50 kHz

The average Inductor Current and output ripple Voltage for both buck and boost operation is no more than 1%.

BATTERY CHARGING MODE

Diode (D) = $\dfrac{V_o}{V_s} = \dfrac{48}{60}$

$\qquad$ = 0.8

Power (P) = $V_o^2 * R$

Resistance (R) = V_o^2 / P

$\qquad$ = $48^2/2000$

$\qquad$ = 1.152Ω

Inductor Current I_L = Output Current I_o

$\qquad$ $I_L = V_o /R$

$\qquad$ = 48 /1.152

$\qquad$ = 41.67A

Average Inductor Current ΔI_L = 1% Inductor Current I_L

$$= 0.4167$$

Average Voltage = 1% Output Voltage V_o

$$= 0.6V$$

Inductor (L) = $\dfrac{(Vs-Vo)D}{\Delta IL*f}$

$$= \frac{(60-48)0.8}{0.4167*50000}$$

$$= 0.4607 \text{ mH}$$

Capacitor (C) = $\dfrac{\Delta IL}{8*f*\Delta V}$

$$= \frac{0.4167}{8*50000*0.48}$$

$$= 2.17 \text{ µF}$$

BATTERY DISCHARGING MODE

Power (P) = $V_o^2 * R$

Resistance (R) = V_o^2 / P

$$= 60^2/2000$$

$$= 1.8\Omega$$

Capacitor (C) = $\dfrac{D}{R*f*(\frac{\Delta Vo}{V})}$

$$= \frac{0.8}{1.8*50000*0.01}$$

$$= 0.888\text{mF}$$

In Discharging mode only resistance and capacitor values change remain all same as a Charging mode. The conditions of the Analytical part of bidirectional converter in buck and boost action are shown in the below table

Table 2. Analysis calculation values of Bidirectional Converter

PARAMETER	ANALYTICAL (BUCK)	ANALYTICAL (BOOST)
RESISTANCE	1.152 Ω	1.8 Ω
INDUCTOR CURRENT	41.19 A	41.19
INDUCTANCE	0.4607 mH	0.4607 mH
CAPACITANCE	2.17 µF	0.2 mF
OUTPUT VOLTAGE	46.08 V	64.23 V

3. Results and discussion

The simulation results for the buck converters and bidirectional converters with the respective peak values are shown below.
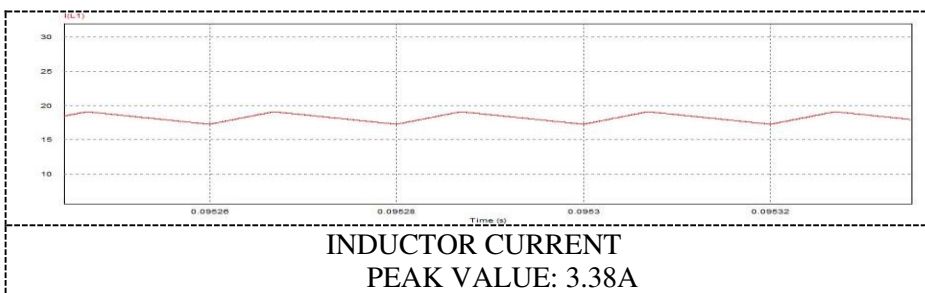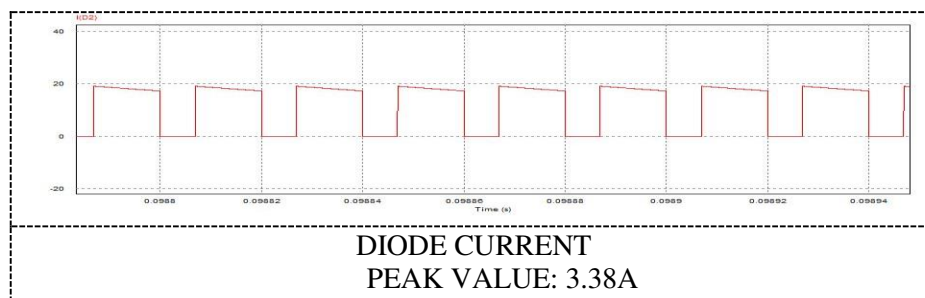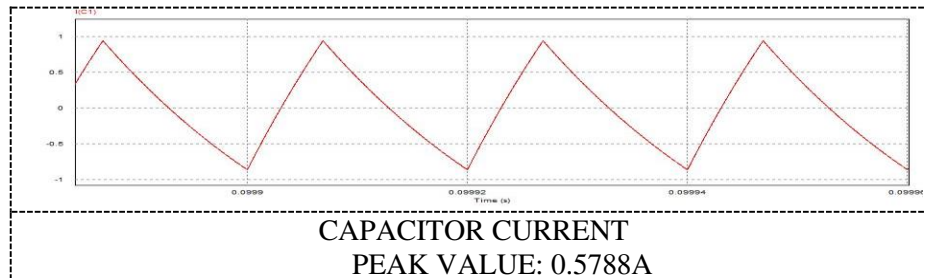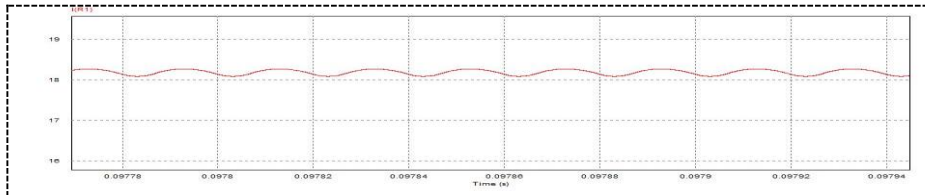
Buck Converter Waveforms

The following table shows the values of the results obtained in simulation using PSIM.

Table 3. Simulation values of Buck Converter

PARAMETER	SIMULATION
CAPACITOR CURRENT	0.05788 A
DIODE CURRENT	3.38 A
INDUCTOR CURRENT	3.38 A
CAPACITOR VOLTAGE	60.2249 V
RESISTOR CURRENT	3.34 A
OUTPUT VOLTAGE	60.2249V

The following waveforms shows the results obtained in simulation using PSIM.

CAPACITOR CURRENT
PEAK VALUE: 0.5788A

DIODE CURRENT
PEAK VALUE: 3.38A

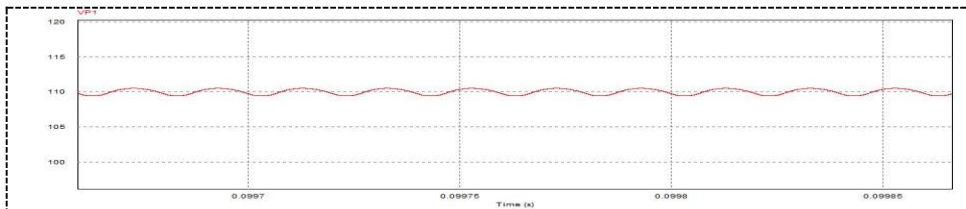INDUCTOR CURRENT
PEAK VALUE: 3.38A

RESISTANCE CURRENT
PEAK VALUE: 3.34A
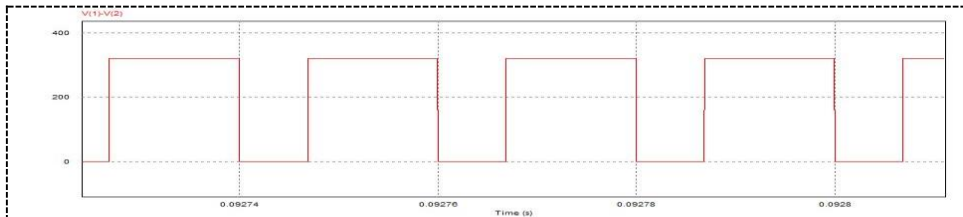

SWITCH CURRENT
PEAK VALUE: 3.38A

OUTPUT VOLTAGE
PEAK VALUE: 60.224V
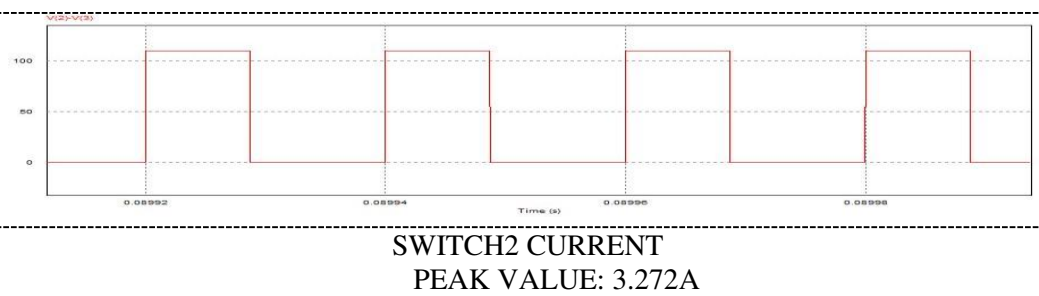
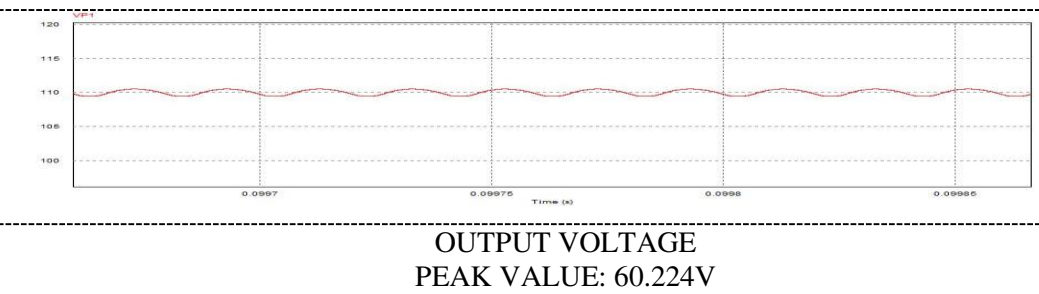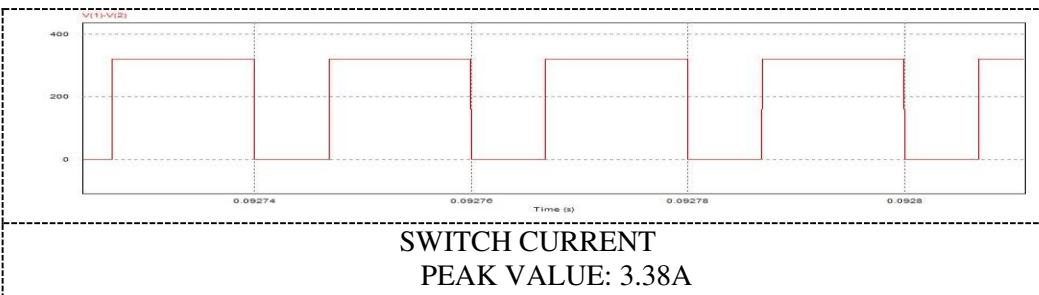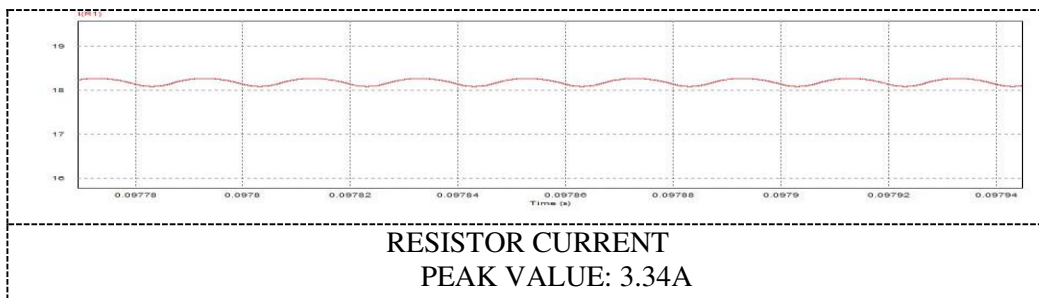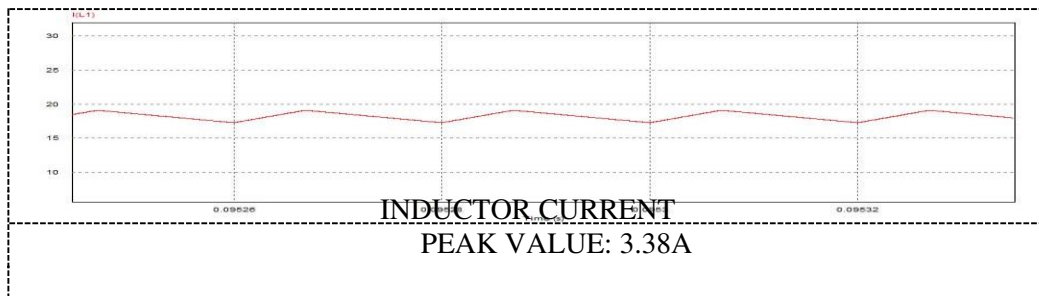**Bidirectional Buck and Boost Converter Waveforms**
The following table shows the results obtained in simulation using PSIM.

CAPACITOR CURRENT
PEAK VALUE: 0.5788A

DIODE CURRENT
PEAK VALUE: 3.38A

INDUCTOR CURRENT

PEAK VALUE: 3.38A

RESISTOR CURRENT

PEAK VALUE: 3.34A

SWITCH CURRENT

PEAK VALUE: 3.38A

OUTPUT VOLTAGE

PEAK VALUE: 60.224V

SWITCH2 CURRENT
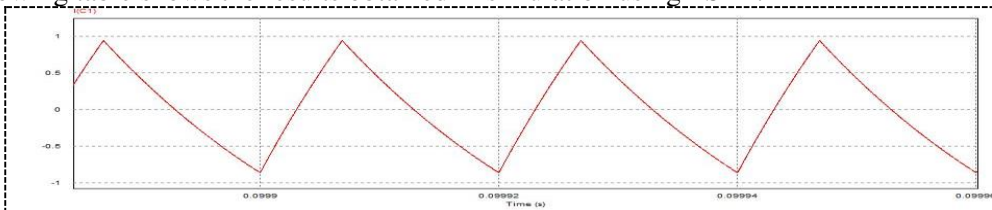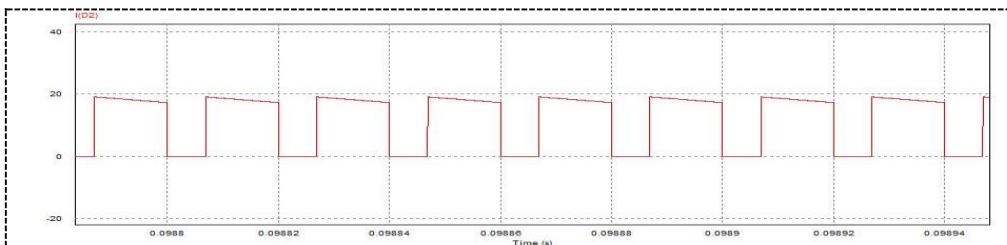
PEAK VALUE: 3.272A

4. Conclusion

The DC-DC converters for the electrical powertrain applications is successfully designed. The results of simulation are in close agreement with the analytical solutions. This validates the credibility of the software. The designed converters consider the AC power grid as the primary source of power. This investigation can further be carried out by the solar source and the converters can be designed as an extension of the same work.

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