

Design and Analysis of Composite Dc-Dc Converter for Electric Vehicle

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Abstract: In a electric vehicle powertrain, a boost dc-dc converter enables reduction of the size of the electric machine and optimization of the battery system. Design of the powertrain boost converter is challenging because the converter must be rated at high peak power, while efficiency at medium to light load is critical for the vehicle system performance. By previously proposed efficiency improvement approaches offer limited improvements in size, cost and efficiency trade-offs. This paper shows how all dominant loss mechanisms in automotive powertrain application can be mitigated using a new composite converter approaches. It is found that the improved composite converter results in a decrease in the total loss. Furthermore, the total system capacitor power rating and energy rating are substantially reduced, which implies potentials for significant reductions in system size and cost.

Keywords: Boost Converter, Composite Converter, DC-DC Converter, Electric Vehicle Powertrain, Improved Composite Converter.

Date of Submission: 18-11-2017

Date of acceptance: 30-11-2017

I. Introduction

A electric vehicle power train includes a battery system, a motor drive system and in some cases, a bidirectional dc-dc converter placed between the battery and the motor drive, as shown in Fig.1 . The boost dc-dc converter enables independent optimization of the battery system and a reduction in the size of the electric machine . The motor-drive dc bus voltage can be increased, which allows extensions of the motor speed range without field weakening. This improves both the motor and the inverter efficiency . The converter can also dynamically adjust the dc bus voltage, so that the system efficiency can be further optimized . The powertrain architecture using a dc-dc converter has been successfully incorporated in commercial vehicle systems .

The losses associated with the boost dc-dc converter must be sufficiently low, so as to not compromise the advantages offered by the powertrain architecture shown in Fig. 1. Designing a high efficiency boost converter in this application is challenging, because the converter must be rated at high peak power, while efficiency at medium to light load is critical for the vehicle system performance. Various approaches have been proposed to improve the boost converter efficiency, including different methods to improve magnetic, and approaches to utilize devices with lower voltage rating.

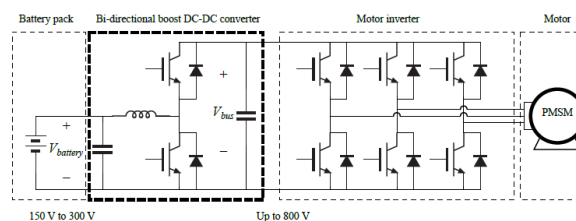


Fig. 1 : Electric Powertrain Architecture

The objective of this paper are to explain the challenges associated with the dc-dc converter design in automotive powertrain applications, to introduce several composite converter topologies.

II. BOOST DC-DC CONVERTER TECHNOLOGY OVERVIEW

Figure 2.1 shows the power stage of a conventional boost converter, realized with IGBT devices. To handle the bi-directional power flow, which is required in traction powertrain application for regenerative brake, the switches Q_1 and Q_2 are realized with an IGBT device together with an anti-parallel diode. If only

unidirectional power flow is required, Q_1 can be realized with a single IGBT device, and Q_2 can be realized with a single diode device.

The switches Q_1 and Q_2 turn on alternatively to chop the inductor current I_{in} , with a switching period T_s . In convention, the turn on duty cycle of switch Q_1 is defined as D. The switch Q_1 voltage and current are sketched in Fig. 2.2.

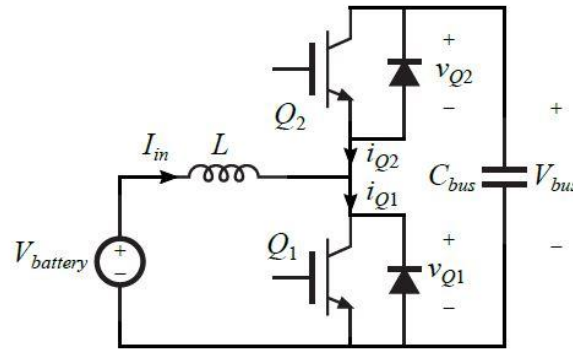


Figure 2.1: Conventional bi-directional boost converter realized with IGBT

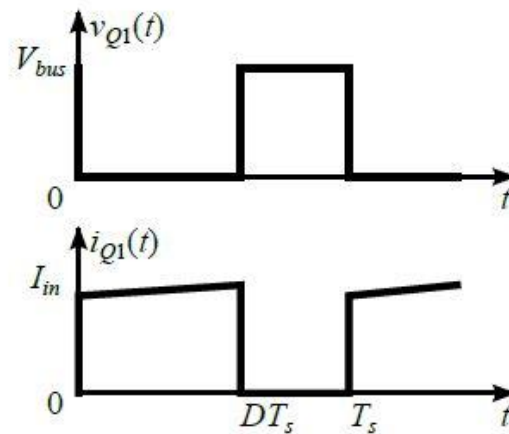


Figure 2.2: Switch Q_1 voltage and current waveforms

If the output capacitor C_{bus} is sufficiently large, one may ignore the output voltage ripple, and assume the output voltage V_{bus} is constant. Under this assumption, the average voltage across the switch Q_1 is:

$$V_{Q1} = (1 - D)V_{bus} = D'V_{bus}, \quad (2.1)$$

where $D' = 1 - D$. The angle brackets that are around V_{Q1} denote the average operation.

Because at steady-state, the inductor L is equivalent to a short circuit, the averaged voltage across the inductor should be zero.

Therefore,

$$V_{battery} = \langle V_{Q1} \rangle = D'V_{bus}. \quad (2.2)$$

Thus, the voltage conversion ratio M of the boost converter can be derived:

$$M = \frac{V_{bus}}{V_{battery}} = \frac{1}{D'} \quad (2.3)$$

The voltage conversion ratio M in (2.3) is solely controlled by the duty cycle command D (or D'). The range of duty cycle D is $0 \leq D \leq 1$, therefore the boost converter can achieve $M \geq 1$. To control the output voltage V_{bus} , the pulse-width modulation (PWM) can be used to modify the duty cycle.

Notice that (2.3) is the ideal relationship between voltage conversion ratio and duty cycle, under the assumption that the output voltage ripple is small, and the system is loss-free. In practice, due to the lossy element in the converter, the voltage conversion ratio M is also a function of output power. In practice, usually the duty cycle D is adjusted with some feedback control to reduce the output impedance of the converter. What is more, due to the loss in the system, the maximum voltage conversion ratio that the system can achieve is always limited.

III. Composite Converter Architecture

To address the mode transition problem of other composite converter, the composite converter is proposed, as shown in Fig. 2.1. A buck converter module is inserted before DCX module to control the DCX output voltage. The buck module output voltage can smoothly ramp down to zero so that the DCX module can be shut down gracefully. If we denote the buck module voltage conversion ratio as $M_{buck}(D_{buck})$, the total system conversion ratio is :

$$\begin{aligned} M &= \frac{V_{bus}}{V_{battery}} \\ &= M_{boost}(D_{boost}) + M_{buck}(D_{buck}) N_{DCX} \end{aligned}$$

It is not necessary to operate all converter modules together.

- When the system voltage conversion ratio M is greater than $1+N_{DCX}$, then the buck module can be operated in pass-through with $N_{DCX}=1$, and the system operates in **DCX+boost** mode.
- When $M < 1+N_{DCX}$, the boost module can be operated in pass-through with $D_{boost}=0$, the system operates in **DCX+buck** mode.

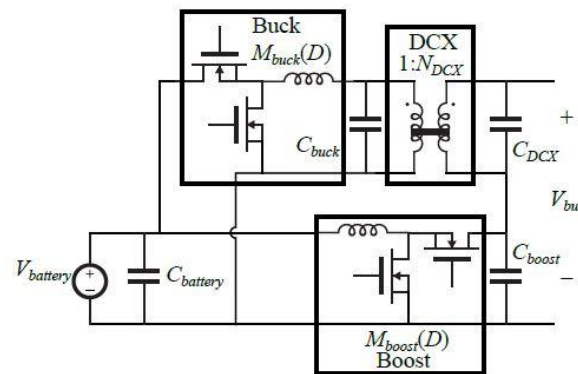


Figure 3.1: Composite converter topology

With the extra buck module, the DCX output voltage can be well controlled, and the dc bus voltage stress can be shared evenly between the DCX and the boost modules. Hence, 600V devices can be employed in all converter modules, with 33% voltage derating. If we define the allowed maximum device voltage stress as V_{Qmax} then

- When the battery voltage $V_{battery} > \frac{V_{Qmax}}{N_{DCX}}$, and the bus voltage $V_{bus} > V_{battery} + V_{Qmax}$, the buck module can limit the DCX output voltage stress to V_{Qmax} , and the system operates in **DCX+buck+boost** mode.
- On the other hand, when $V_{bus} \leq V_{Qmax}$, the system can operate in **boost** mode only mode to improve efficiency at low voltage conversion ratios.

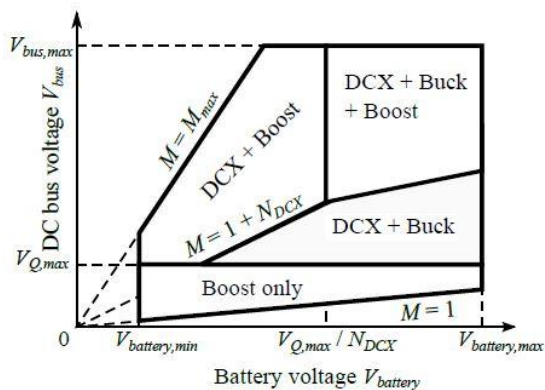


Figure 3.2: Composite converter operating modes

PARAMETER	VALUES
Capacitor	222e-6 F
Inductor	72e-6 H
Switching Frequency	20 KHz

Table 3.1: Parameters used in Boost Stage

PARAMETER	VALUES
Capacitor	300e-6 F
Inductor	72e-6 H
Switching Frequency	20 KHz

Table 3.2: Parameters used in Buck Stage

PARAMETER	VALUES
Capacitor	100e-6 F
Tank Inductor	4e-6 H
Switching Frequency	30KHz
Transformer Turns ratio	1:2

Table 3.3: Parameters used in DCX Stage

IMPROVED COMPOSITE CONVERTER

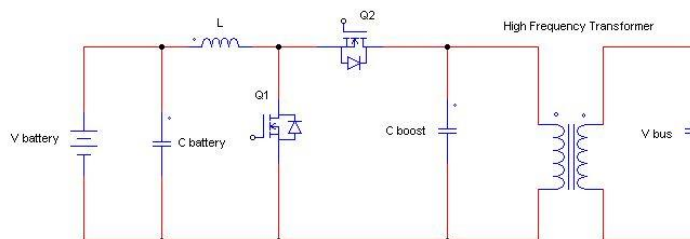


Figure 3.3: Improved Composite converter topology

Fig. 3.3 shows a boost composite converter based on , but with a boost converter module inserted to control the DCX voltage, if we denote the boost converter voltage conversion ratio as $M_{boost}(D_{boost})$, and DCX turns ratio as N_{DCX} , then the two converters in series have the total voltage conversion ratio of

$M_{boost}(D_{boost})N_{DCX}$, which emulates the duty cycle controlled ideal dc transformer in Fig. 3.1. The overall voltage conversion ratio of this improved composite converter is:

$$M = \frac{V_{bus}}{V_{battery}} = M_{boost}(D_{boost}) N_{DCX}$$

The boost module is operated as boost module for $D_{boost} > 1$. This results in much higher efficiency than operating the module as a boost with two devices switching.

The Improved Composite converter inherits the merits from the configuration in Fig. 3.3. The direct power path is a direct loss-free short-circuit connection. However, similar to the configuration in Fig.3.4, although this configuration does reduce the device voltage stress, the reduction is not sufficient to facilitate devices with much lower voltage rating. For example, when the battery voltage is 200V, if 800V is desired at the dc bus output, the boost as well as DCX produce 800V output. In this case, 900V or 1200V devices would be required.

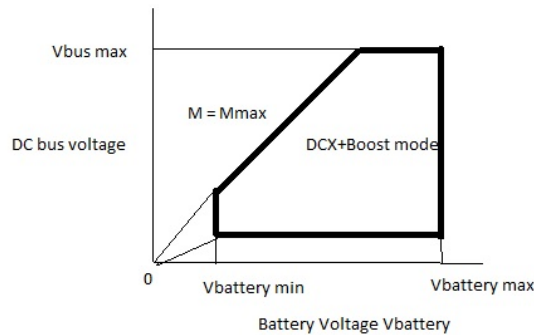


Figure 3.4: Improved Composite converter operating modes

PARAMETER	VALUES
Capacitor	222e-6 F
Inductor	72e-6 H
Switching Frequency	20 KHz

Table 3.4: Parameters used in Boost Stage for Improved Composite Converter

PARAMETER	VALUES
Capacitor	100e-6 F
Tank Inductor	4e-6 H
Switching Frequency	30KHz
Transformer Turns ratio	1:2

Table 3.5: Parameters used in DCX Stage for Improved Composite Converter

IV. Design and simulation results

DESIGN OF COMPOSITE AND IMPROVED COMPOSITE CONVERTER

4.1 COMPOSITE CONVERTER

FOR BOOST STAGE

Given:

Input Voltage = 200 V and

Duty cycle = 50%.

Formula:

$$V_{out} = V_{in} \frac{1}{1-\alpha}$$

$$V_{out} = 400 V$$

FOR BUCK STAGE

Given:

Input Voltage = 200 V and
Duty cycle = 50%.

Formula:

$$V_{out} = \alpha V_{in}$$

$$V_{out} = 100V$$

FOR DC TRANSFORMER

Given:

Input Voltage = 100 V and

Transformer turns ratio = 1: N_{DCX}

where $N_{DCX} = 2$

Formula:

For Passive Rectification ,

$$V_{out} > V_{in} N_{DCX}$$

$$V_{out} > 200V$$

Operating condition: (Based on Voltage Conversion ratio)

- $N_{DCX} = 2$

then $M = \frac{V_{bus}}{V_{battery}}$

$$M = \frac{620.3}{200} = 3.1015$$

$$M > 1 + N_{DCX}$$

So, the system operates in **DCX + boost mode**.

Operating condition: (Based on Voltage Stress)

- $V_{Qmax} = 400V$

$$V_{battery} = 200V$$

$$N_{DCX} = 2$$

$$V_{bus} > V_{battery} + V_{Qmax}$$

$$V_{bus} = 620V$$

So, the system operates in **DCX+boost+buck mode**.

4.2 IMPROVED COMPOSITE CONVERTER FOR BOOST STAGE

Given:

Input Voltage = 200 V and

Duty cycle = 50%.

Formula:

Input Voltage = 200 V and

Duty cycle = 50%.

Formula:

$$V_{out} = V_{in} \frac{1}{1-\alpha}$$

$$V_{out} = 400V.$$

FOR DC TRANSFORMER

Given:

Input Voltage = 100 V and

Transformer turns ratio = 1: N_{DCX}

where $N_{DCX} = 2$

Formula:

$$V_{out} = N_{DCX} V_{in}$$

$$V_{out} = 2 * 400$$

$$V_{out} = 800V.$$

OPERATING CONDITION (BASED ON VOLTAGE CONVERSION RATIO)

- $N_{DCX} = 2$
then $M = \frac{V_{bus}}{V_{battery}}$
 $M = \frac{800}{200} = 4$
 $M > N_{DCX}$

So, the system operates in **DCX + boost mode**.

SIMULATION RESULTS

COMPOSITE DC-DC CONVERTER

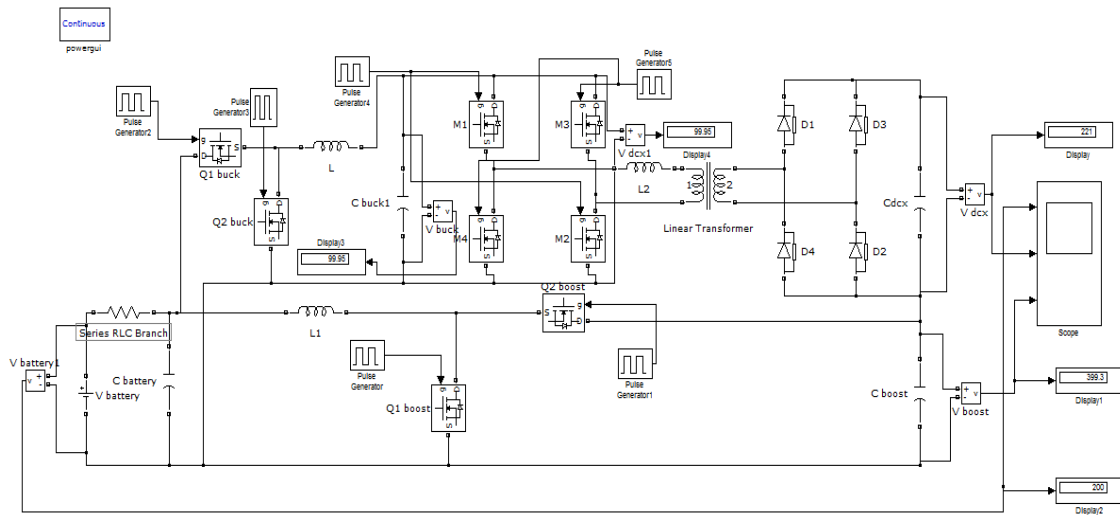


Figure 4.1 : Simulation diagram of Composite DC-DC Converter

WAVEFORM FOR COMPOSITE DC-DC CONVERTER

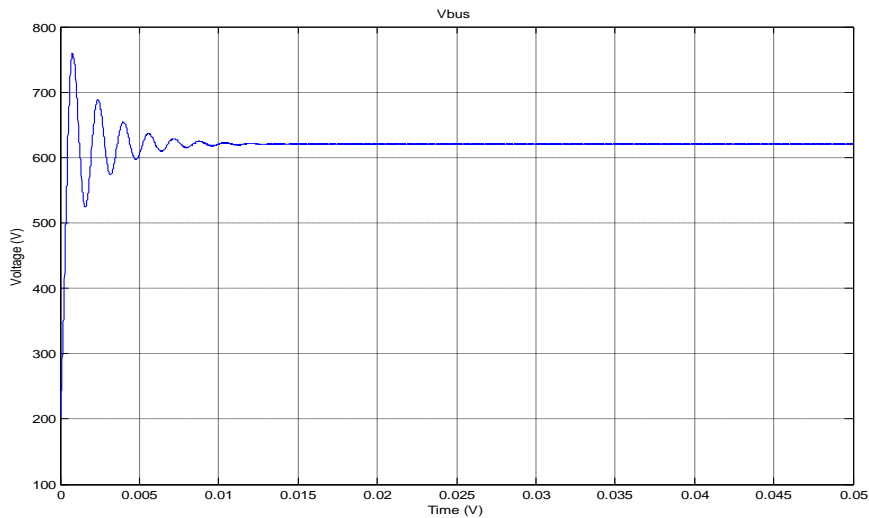


Figure 4.2: Waveform for Composite DC-DC converter

IMPROVED COMPOSITE CONVERTER

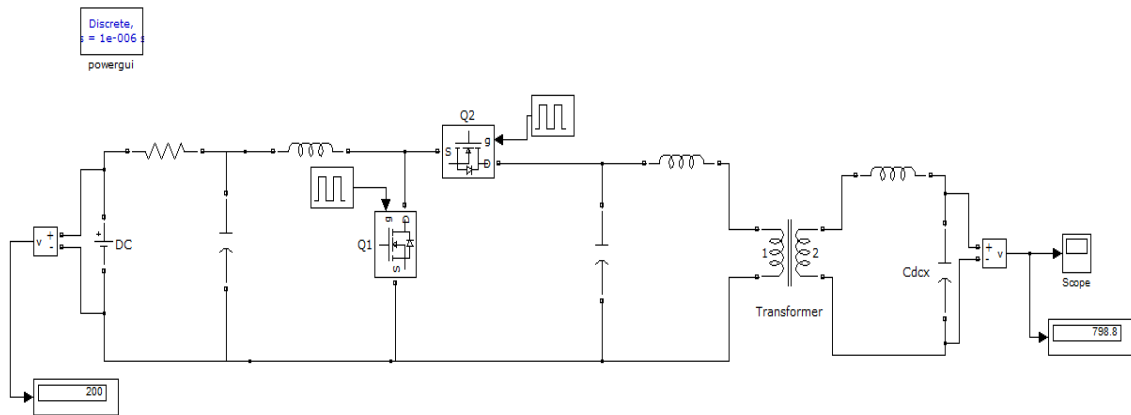


Figure 4.3: Simulation diagram of Improved Composite DC-DC Converter

WAVEFORM

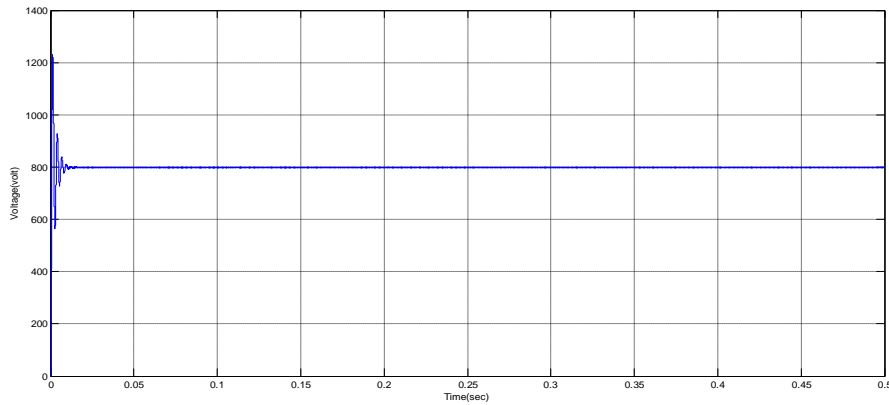


Figure 4.4: Waveform for Improved Composite DC-DC Converter

IMPROVED COMPOSITE SYSTEM WITH INVERTER CIRCUIT

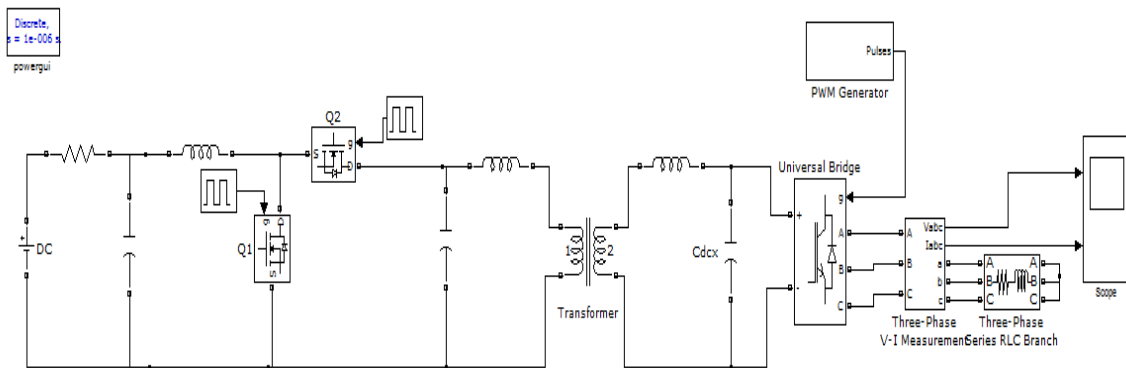


Figure 4.5: Simulation diagram of Improved Composite DC-DC Converter system with Inverter circuit

WAVEFORM

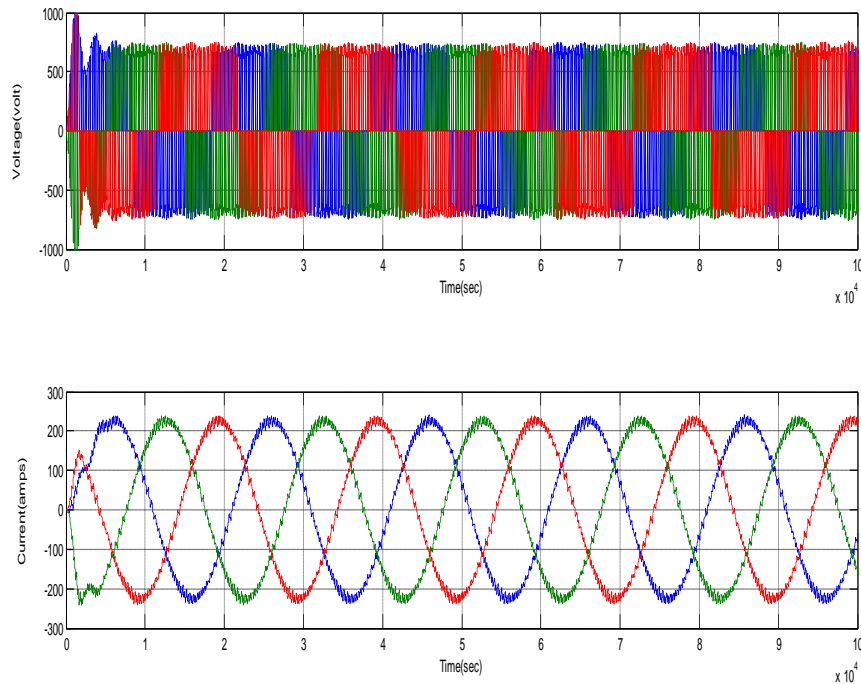


Figure 4.6: Waveform for Improved Composite DC-DC Converter system with Inverter circuit

V. Conclusion

In a electric vehicle powertrain, a boost dc-dc converter enables reduction of the size of the electric machine and optimization of the battery system. In this work, the improved composite dc-dc architecture is proposed, it results in a decrease in the total loss by a factor of two to four for typical drive cycles. Furthermore, the total system capacitor power rating and energy rating are substantially reduced, which implies potentials for significant reductions in system size and cost.

Two different composite converter architectures are proposed, and the improved composite converter exhibits superior performance over various previous approaches. Because of the dedicated indirect power path, the composite converter can significantly reduce the capacitor rms current rating as well, which leads remarkable capacitor module size and cost reduction

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IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) is UGC approved Journal with Sl. No. 4198, Journal no. 45125.

Sowmiya .P Design and Analysis of Composite Dc-Dc Converter for Electric Vehicle." IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), vol. 12, no. 6, 2017, pp. 01-10