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Closed Loop Control 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 and the closed loop control of composite dc-dc converter enables to get constant DC output at converter terminal. It is found that the selected 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, Closed loop control, Composite Converter, DC-DC Converter, Electric Vehicle Powertrain*

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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.

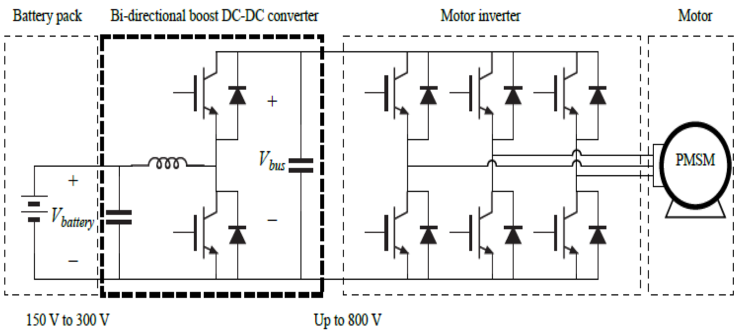

Fig. 1 : Electric Powertrain Architecture

The objective of this paper are to explain the challenges associated with the dc-dc converter design in automotive powertrain applications and the closed loop control of composite dc-dc converter enables to get constant DC output at converter terminal.

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.

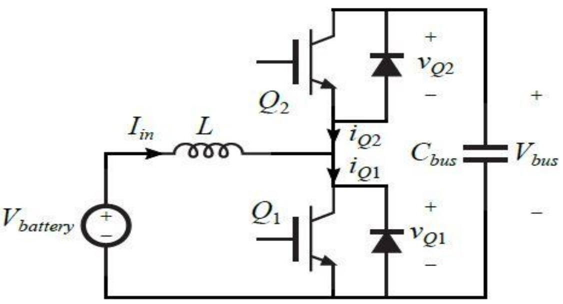

Figure 2.1: Conventional bi-directional boost converter realized with IGBT

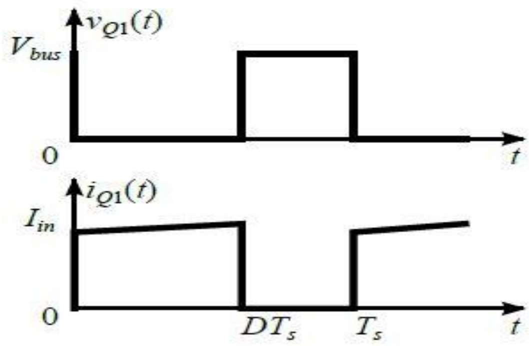

Figure 2.2: Switch Q_1 voltage and current waveforms

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:

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

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,

$$V_{battery} = < V_{Q1} > = D^{'}V_{bus}. \qquad (2.2)$$

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

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

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 ≤ D ≤ 1, therefore the boost converter can achieve M ≥ 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 :

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

3.1 It is not necessary to operate all converter modules together.

1. 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.
2. 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.

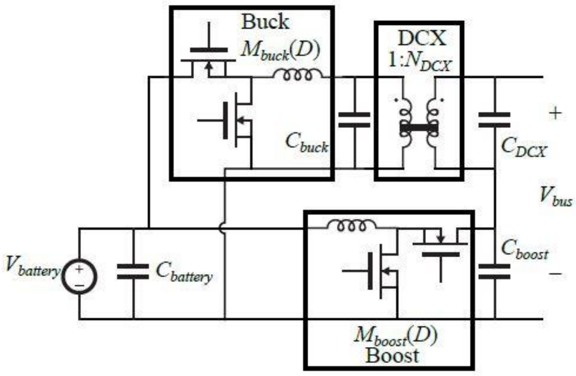

Figure 3.1: Composite converter topology

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

1. When the battery voltage $V_{battery} > {V_{Qmax}}/{N_{DCX}}$, 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.
2. 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.

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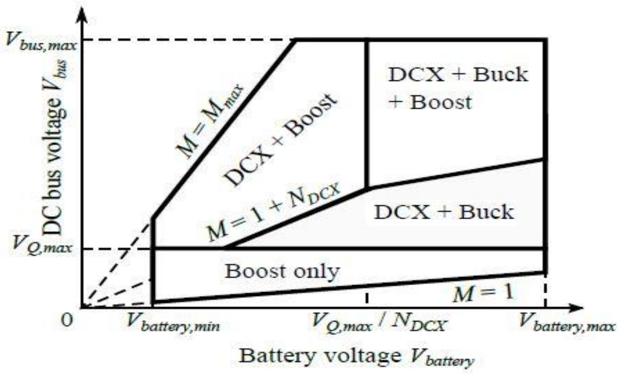

Figure 3.2: Composite converter operating modes

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

3.1 Control Of Composite Dc-Dc Converter

The previous chapter verifies the efficiency improvements of the composite converter architecture, with open-loop operation. This chapter introduces a possible control architecture for the composite converter, which verifies its controllability. Because the composite architecture requires controlling several converter modules at the same time, the conventional control architecture no longer apply. On the other hand, to further enhance the system efficiency, each module may operate at pass-through or shut-down mode at certain operating conditions, resulting several system operation modes. In this chapter, a novel centralized control algorithm is proposed. It is able to regulate system output voltage, while optimizing the system efficiency by automatically and smoothly transits the system into corresponding operating mode that yields the best efficiency. It also protects the converter modules from over voltage or over current stress. This control method combines several conventional control techniques, such as average current control and PI compensator. Therefore, it is relatively simple, and can be implemented into some inexpensive hardware.

3.2 proposed Control Algorithm

The main system control objective is to regulate the output voltage V_{out} at a reference voltage level. The closed-loop control system is expected to achieve high-performance static and dynamic regulation with respect to variations in commanded reference level, and in the presence of disturbances such as load or input voltage variations. The controller should further automatically adjust the system operating mode to optimize the system efficiency, and to ensure that all devices operate within safe operating limits. Therefore, the controller should be able to control the system so that the steady-state mode is the same.

Although the composite converter system is composed of several converter modules, a centralized control algorithm that can be implemented onto a single micro-controller unit is preferred, to reduce control complexity.The composite converter system has several operation modes. To achieve mode transitions, look-up table or logic-basic mode decision methods may be employed. However, such approaches can easily lead to discontinuities across mode boundaries and undesirable mode-transition disturbances. The control architecture and the control algorithm developed are instead designed to achieve smooth mode transitions.

3.3 The control signals available to the composite converter system controller are:

1. Buck module duty cycle D_{buck}, $0 \leq D_{buck} \leq 1$, where $D_{buck} = 1$ corresponds to pass-through operation of the buck module, and $D_{buck} = 0$ corresponds to shut-down operation of the buck module.
2. Boost module duty cycle D_{boost}, $0 \leq D_{boost} \leq 1$, $D_{boost} = 0$ corresponds to pass-through operation of the boost module.
3. DCX module on\off control signal DCX enable. When DCX module turns on, it is only operated in open-loop with fixed 50% duty cycle. Therefore, DCX will not operate in those regions that the voltage conversion ratio significantly deviates from transformer turns ratio, which results in much lower efficiency.

3.4 To achieve the closed-loop control objectives, the following signals are sensed by the controller:

1. The output voltage V_{out} , to achieve the main voltage regulation control objective.
2. The boost module output voltage V_{boost} is sensed, and the DCX output voltage is calculated as

$$V_{DCX} = V_{bus} - V_{boost}$$

The output voltages of the boost and DCX modules are limited to a maximum of V_{Qmax} , to ensure that the voltage stresses applied to devices remain within safe derated levels.

3.5 PI Controller Implementation

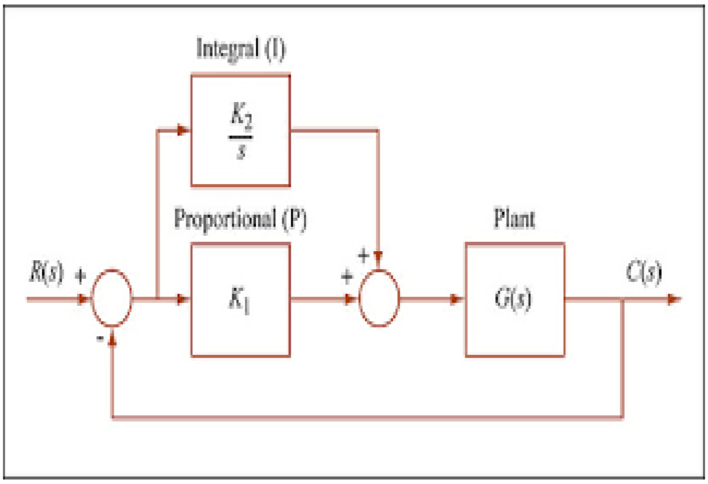

Figure 3.3: Block diagram of PI controller

A PI controller calculates an error value as the difference between a measured process variable and desired set point. The controller attempts to reduce the error by adjusting the process through the use of a manipulated variable. Fig. 3.1 shows the basic block diagrams of the PI controller.The error values are calculated via sensor or transducer and compared with desire set point. The detection is in terms of voltage, current, temperature, movement, angle and etc. The PI controller is adjusted manually by setting the value of K_i is equal to zero.

The value of K_p is manually tuned based on Ziegler Nichols Method in order to eliminate any error between the set-point and process variable instantly. The PI controller will ensure the Boost converter delivers a sufficient amount of voltage to the load and also for Buck converter. By increasing the value of K_i the system until the offset, it will decrease the rise time of the system. However, the system will become unstable and the overshoot will be increased. The value of K_i must be adjusted in certain amount to make sure the system endure the overshoot while decreasing the settling time and keeping the stability. The derivation of the PI controller is obtained as follow:

$$u(t) = K_p(t) + K_i \int_0^t e(\tau)\ dt$$

The output voltage was compared with the constant input voltage to produce an error. Afterward, the error was connected to the PI block and the output was then compared with the saw tooth signal to generate an equivalent duty cycle which was used to drive the switching devices of the converters.

IV. Design And Simulation Results

Design Of Closed Loop Composite Converter
4.1 Composite Converter
For Boost Stage
Given:
Input Voltage = 200 V and
Duty cycle = 50%.
Formula:

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

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

4.2 For Buck Stage
Given:
Input Voltage = 200 V and
Duty cycle = 50%.
Formula:

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

$$V_{out} = 100V$$

4.3 For Dc Transformer
Given:
Input Voltage = 100 V and
Transformer turns ratio = 1: N_{DCX}
where N_{DCX} = 2
Formula:
For Passive Rectification ,

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

$$V_{out} > 200V$$

4.4Operating 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**.

4.5 Operating condition: (Based on Voltage Stress)

- $V_{Qmax} = 400V$

  $V_{battery} = 200V$

  N_{DCX} = 2

  $V_{bus} > V_{battery} + V_{Q\ max}$

  $V_{bus} = 620V$

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

4.6 Closed Loop Controller For Composite Converter:
Ziegler Nichols Method

Control Type	Kp	Ki	Kd
P	0.5Kc	-	-
PI	0.45Kc	Pc/1.2	-
PID	0.6Kc	2Kp/Pc	KpPc/8

Table 4.1: Ziegler Nichols Method
Where Kc = Converter gain
Kp = Proportional gain
Ki = Integral gain

4.7 For Pi Controller For Boost Converter
Kp = 0.45 Kc
Kc = (Output Voltage) / (Input Voltage)
Kc=400/200=2.
where Kp = 0.45*2
Kp = 0.9.
Ki = Pc/1.2
Pc = 1/(20K) = 5e-5
Ki = 5e-5/1.2
Ki= 4.167e-5.

4.8 For Pi Controller For Buck Converter
Kp = 0.45 Kc
Kc = (Output Voltage) / (Input Voltage)
Kc=100/200=0.5.
where Kp = 0.45*0.5
Kp = 0.225.
Ki = Pc/1.2
Pc = 1/(20K) = 5e-5
Ki = 5e-5/1.2
Ki = 4.167e-5.

V. Simulation Results

5.1 Composite Dc-Dc Converter

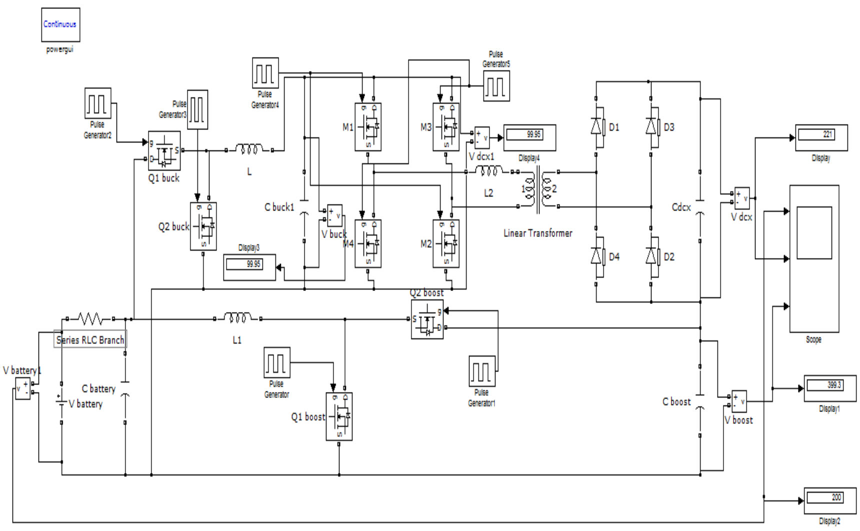

Figure5.1:SimulationdiagramofCompositDC-DCConverter

5.2 Waveform For Composite Dc-Dc Converter

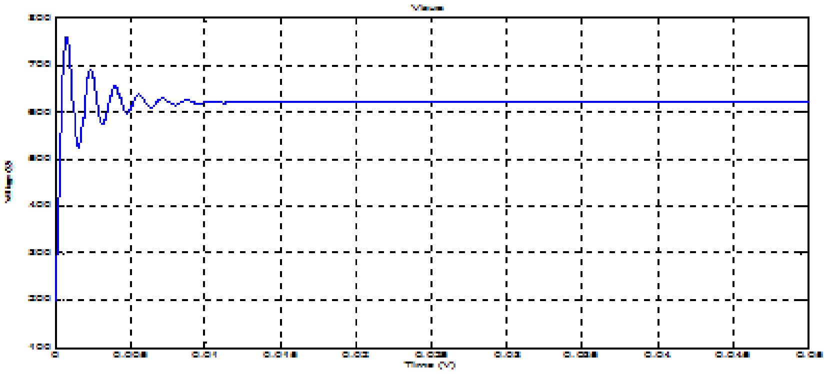

Figure 5.2: Waveform for Composite DC-DC converter

5.3 Closed Loop Controller For Boost Converter

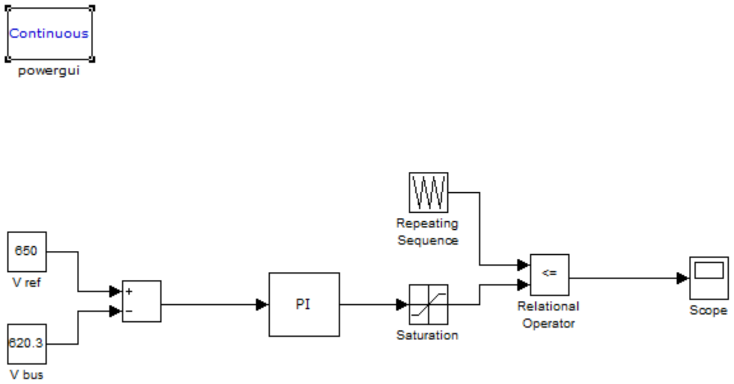

Figure 5.3: Simulation diagram of Closed Loop Controller for Boost Converter

5.4 Waveform

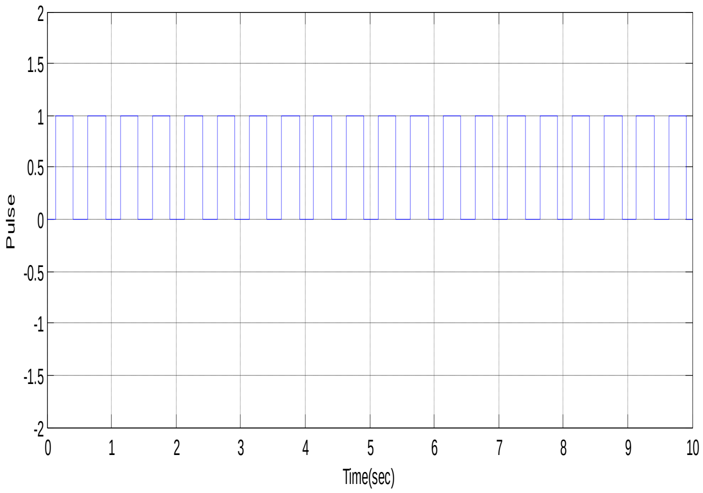

Figure 5.4: Waveform for Closed Loop Controller for Boost Converter

5.5Closed Loop Controller For Buck Converter

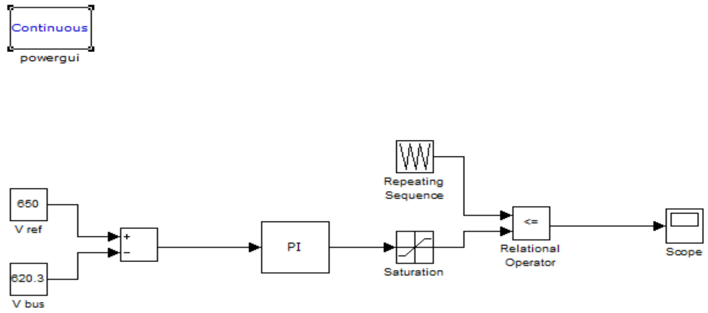

Figure 5.5: Simulation diagram of Closed Loop Controller for Buck Converter

5.6 Waveform

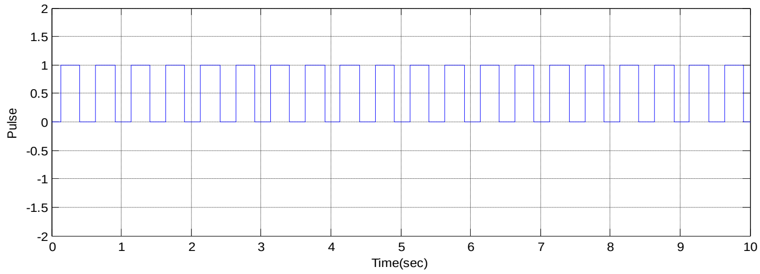

Figure 5.6: Waveform for Closed Loop Controller for Buck Converter

5.7 Closed Loop Controller For Composite Dc – Dc Converter

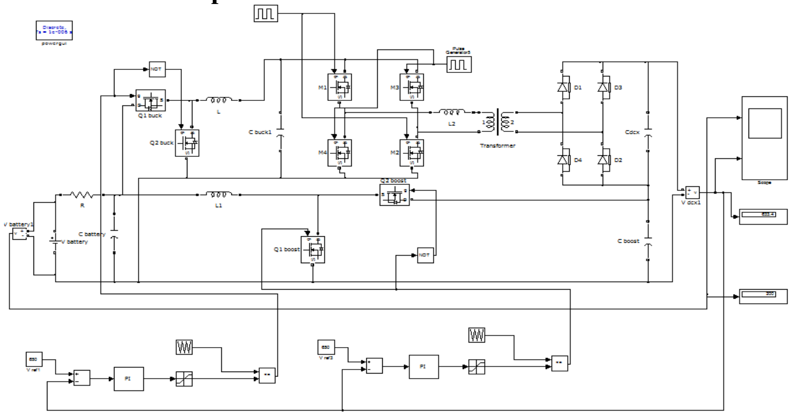

Figure 5.7: Simulation diagram of Closed Loop Controller for Composite DC-DC Converter

5.8 Waveform

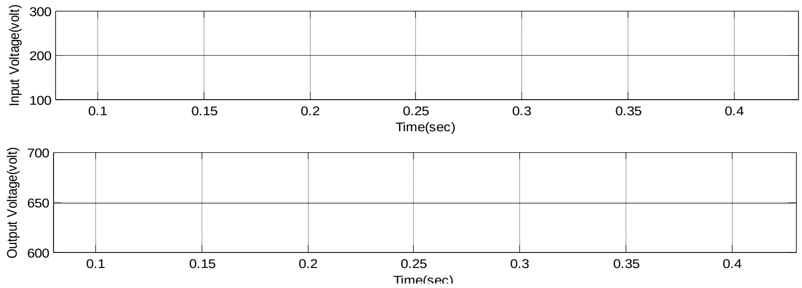

Figure 5.8: Waveform for Closed Loop Controller for Composite DC-DC Converter

VI. Conclusion

In a hybrid or 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 composite dc-dc architecture is proposed, which has fundamental efficiency improvements over wide ranges of operating conditions. 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.

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