Design of DC-DC converters for on-board charging applications

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Abstract: **Climate change and the greenhouse effect are the major motivational factors for the development of electric transportation systems word wide. The major components in electric vehicles are the motor, energy storage system, and control circuits. Out of all the major research areas in current trend are the charging technologies. Various charging techniques available are static charging, dynamic charging, etc.**

Using the charging circuits of an electric vehicle, the power can be transferred from grid to vehicle and also from vehicle to grid. The power flow will be from the grid to the vehicle if the battery storage is less. But, it is possible to send back the power from vehicle to grid if the bidirectional charging circuit is employed in the vehicle. This requirement can be utilized during the lack of power produced by renewable energy sources.

In this paper, a bi-directional charging circuit for electric vehicles is designed and simulated. The charging circuit can send and receive the power in both directions. The simulation results of the charging circuit are shown and the waveforms related to the charging and discharging are also shown. Entire simulations are performed in SIMULINK.

***Keywords*: Bi-Directional, Charging, Grid, Battery, Electric Vehicle.**

1. INTRODUCTION

The following survey reflects the importance of charging technologies in the operation of electrical vehicles. It shows the major customer interest during the purchase of any electric vehicle.

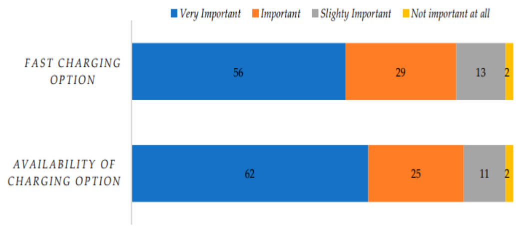


Fig.1. Influence of charging option.

Most of the people who buy an electric vehicle, the major limitation is the charging circuit, because everyone requires a fast charging mechanism. Following are the various charging mechanisms available for electric vehicles. They are

1. Static charging
2. Dynamic charging
3. Fast charging

The static charging technology is to charge the vehicle at rest position, whereas using dynamic charging, the vehicle is charged under running conditions also. But there are a lot of constraints to implement dynamic charging techniques.

Following are the vehicle charging circuits available for the electrical vehicle.

1.1 Grid to vehicle/ Vehicle to grid Charger:

This type of charging circuit is becoming very popular due to the bidirectional transfer of power. The power can be transferred from vehicle to grid and also from the grid to vehicle. The vehicle to grid mode is utilized if the renewable energy availability is reduced.

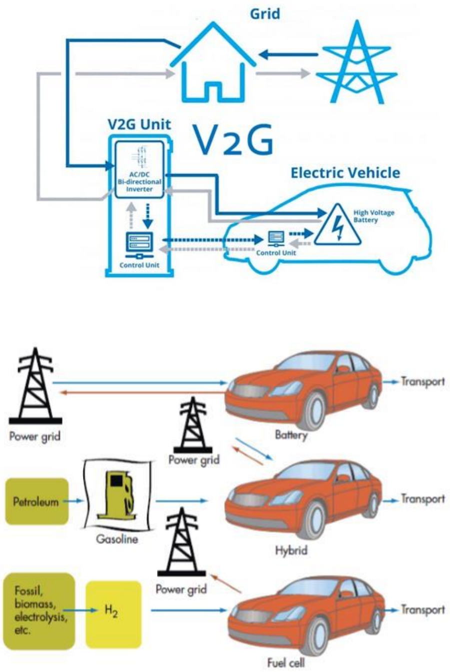


Fig.2. Vehicle to grid and grid to vehicle

1.2 On-Board bidirectional charger**:**

This type of charging technique is also becoming very popular, as the power flow is bidirectional.

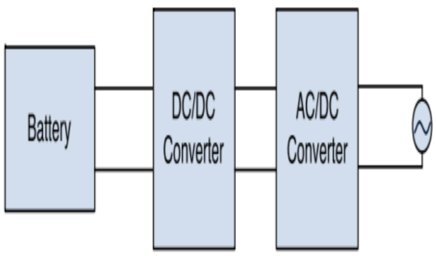


Fig.3. Typical Bidirectional charger.

1.3 Grid Synchronization:

This is the instantaneous solution to charge the electric vehicle; The method used to charge utilized the phase-locked loop using this technology.

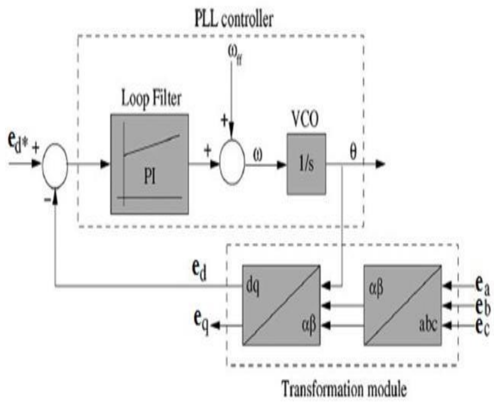


Fig.4. Grid Synchronization.

2. LITERATURE REVIEW

In this section, the related work that is presented in the open literature is shown. Some of the good aspects related to the onboard DC-DC converters are highlighted. The structure, topologies, and the control issue of various available converters are included here in this chapter.

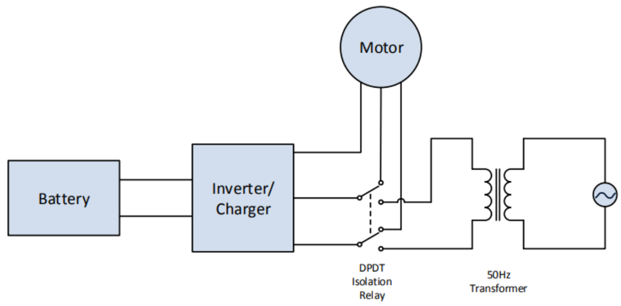


Fig.5. Bidirectional converter topology for charging circuits.

Following are the major areas that are carried out research related to the onboard charging circuit.

- Active power decoupling technique.
- Advanced control methods of converters.
- The advanced topologies of converter circuits.
- Multi-functional onboard dc-dc charging circuits.

Simple bi-directional AC to DC converter:

It consists of two modules, which are shown below figure.

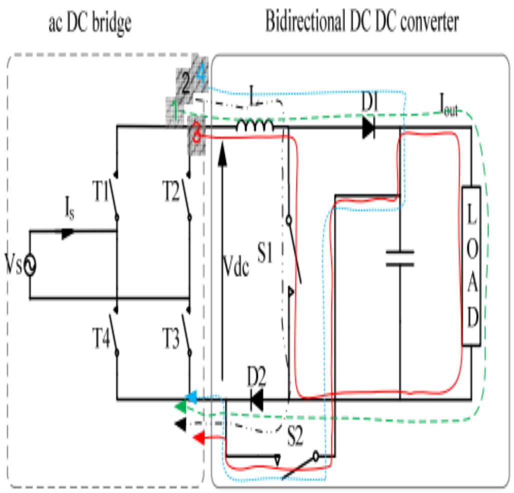


Fig.6. Simple AC to DC converter.

3.CONVERTERS FOR CHARGING CIRCUITS

The dc-dc converter plays a vital role in the charging process of electric vehicles. It provides a good interface for the vehicle and the power source. In this chapter, various dc-dc converters that are used in the design of the charging circuit are presented. The topology and the design of various converters are also included.

3.1 Types of DC-DC converters:

Following are the various types of DC-DC converters that are used for electric vehicle charging applications.

- Buck converter
- Boost converter
- Buck/Boost converter
- Cuk converter
- SEPIC converter
- Resonant converter.

Out of all, In the present discussion, the converters used for charging applications are considered.

3.2 Buck, Boost, Buck/Boost converter:

To increase or to decrease the voltage these types of converters are used. These converters are more popular due to their simplicity.

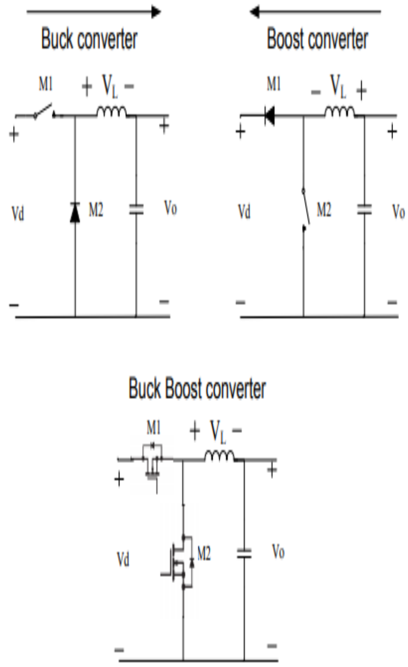


Fig.7. Buck, Boost converters.

3.3 DC-DC Full bridge converters:

These converters can be derived from buck converters, the voltage source is required for this type of converters. These are also called voltage source converters. The below figure shows the topology of this converter.

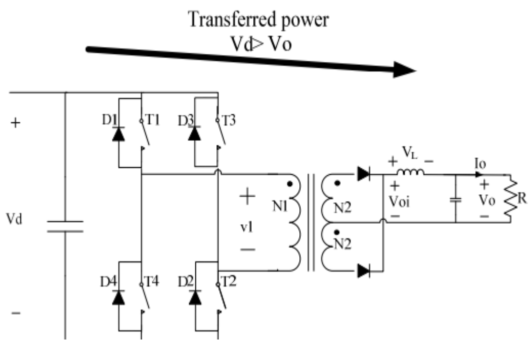


Fig.8. DC-DC full-bridge converter.

The operating equations of this converter are shown below.

$$
\begin{cases}
T1, T2: on \rightarrow v_{oi} = \dfrac{N2}{N1} V_d \rightarrow v_L = \dfrac{N2}{N1} V_d - V_o \\
All\ switches: off \rightarrow v_{oi} = 0 \rightarrow v_L = -V_o \\
T3, T4: on \rightarrow v_{oi} = \dfrac{N2}{N1} Vd \rightarrow v_L = \dfrac{N2}{N1} V_d - V_o \\
All\ switches: off \rightarrow v_{oi} = 0 \rightarrow v_L = -V_o
\end{cases}
$$

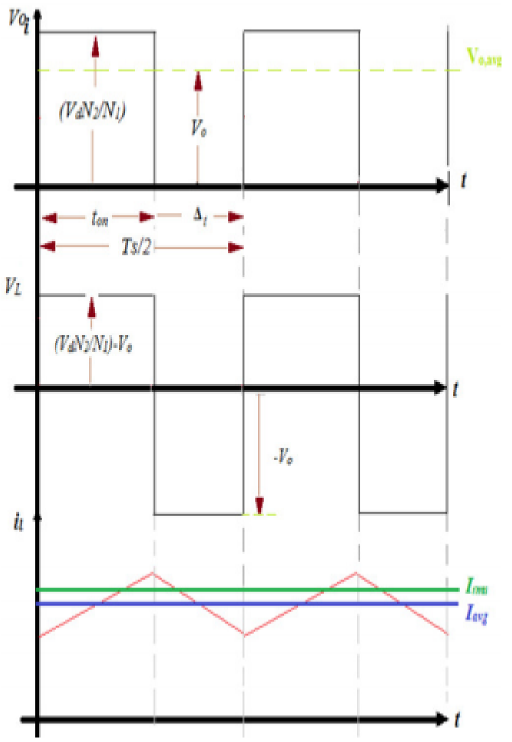


Fig.9. Waveforms of Full bridge converter.

3.4 Full bridge current source converters (FBCSC):

An inductor is added at the input to operate this converter for the entire range of the duty cycle. The topology of the circuit is shown below.

$$\begin{cases} T'1, T'2: on \rightarrow v_1 = \frac{N1}{N2} V_o \rightarrow v_L = V_d - \frac{N1}{N2} V_o \\ All\ switches:\ on \quad \rightarrow \quad v_L = V_d \\ T'3, T'4: on \rightarrow v_1 = \frac{N1}{N2} V_o \rightarrow v_L = V_d - \frac{N1}{N2} V_o \\ All\ switches:\ on \quad \rightarrow \quad v_L = V_d \end{cases}$$

$$\frac{Vo}{Vd} = \frac{N2}{N1} \frac{1}{2(1-D)}, \quad D > 0.5$$

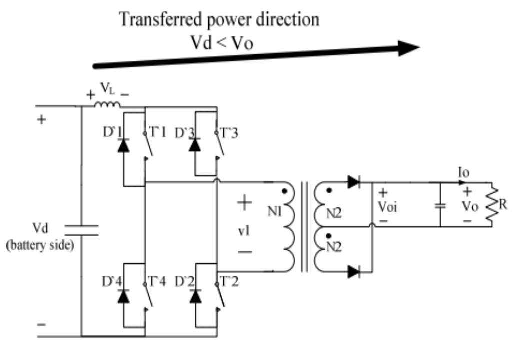


Fig.10. Topology of FBCSC.

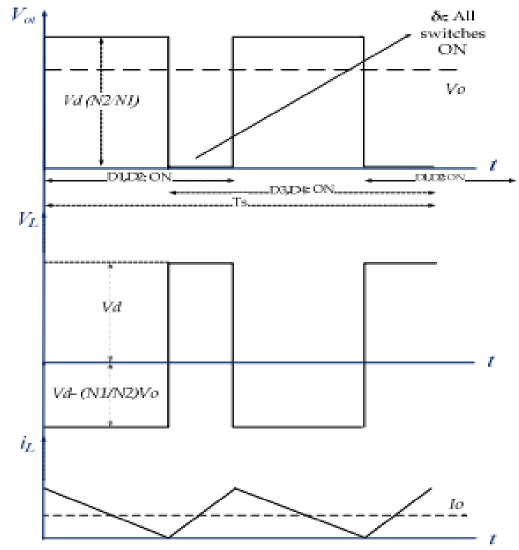


Fig.11.Waveforms of FBCSC.

3.5 Bi-Directional Double leg Full-Bridge Converter:

The combination of a full-bridge voltage source converter and the full-bridge current source converter will give this topology. The circuit diagram and the operating equations are shown below.

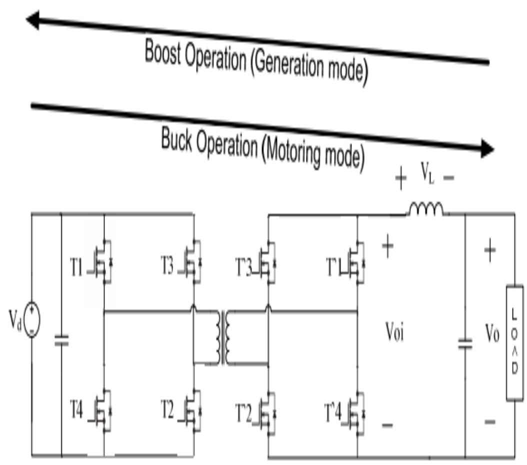


Fig.12. Topology of double leg full-bridge converter.

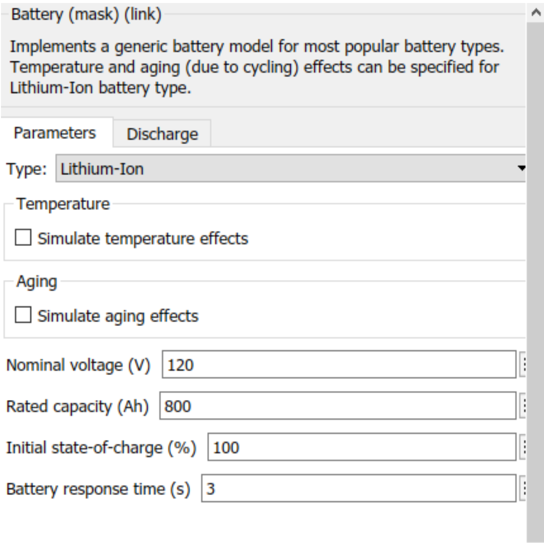
$$\begin{cases} T'1, T'2: on \rightarrow v_L = V_o - \frac{N1}{N2} V_d \\ All\ switches: on \rightarrow v_L = V_o \\ T'3, T'4: on \rightarrow v_1 = \frac{N1}{N2} V_o \rightarrow v_L = V_o - \frac{N1}{N2} V_d \\ All\ switches: on \rightarrow v_L = V_o \end{cases}$$

4. SIMULATION MODEL AND RESULTS

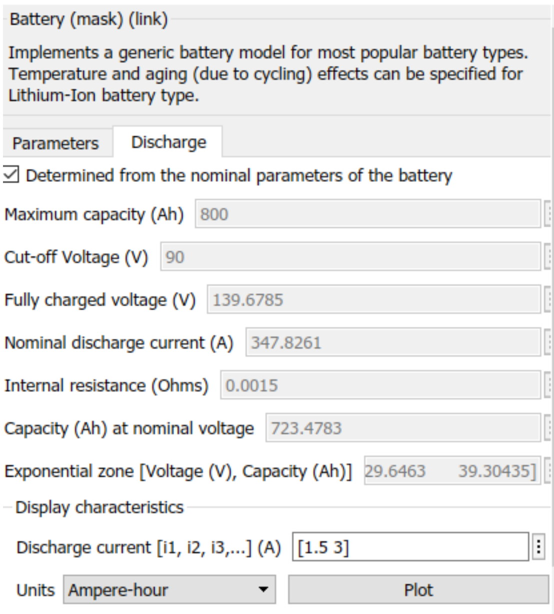
In this section, the simulation results that are obtained for the proposed bidirectional dc-dc converter are presented. All the simulations are carried out in MATLAB/SIMULINK. All the output waveforms are shown for both directions of the power flow.

4.1 Specifications:

Battery Specifications:


Battery (mask) (link)
Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.
Parameters | Discharge
Type: Lithium-Ion
Temperature
☐ Simulate temperature effects
Aging
☐ Simulate aging effects
Nominal voltage (V) 120
Rated capacity (Ah) 800
Initial state-of-charge (%) 100
Battery response time (s) 3

Following are the Battery Discharge parameters:


Battery (mask) (link)
Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.
Parameters | Discharge
☑ Determined from the nominal parameters of the battery
Maximum capacity (Ah) 800
Cut-off Voltage (V) 90
Fully charged voltage (V) 139.6785
Nominal discharge current (A) 347.8261
Internal resistance (Ohms) 0.0015
Capacity (Ah) at nominal voltage 723.4783
Exponential zone [Voltage (V), Capacity (Ah)] 29.6463 39.30435]
Display characteristics
Discharge current [i1, i2, i3,...] (A) [1.5 3]
Units Ampere-hour | Plot

4.2 Simulation Model:

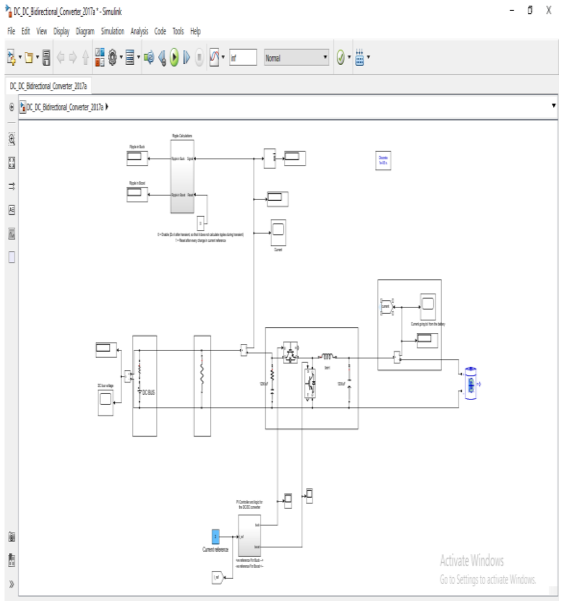


Fig.13. Simulation circuit of Bi-directional Converter.

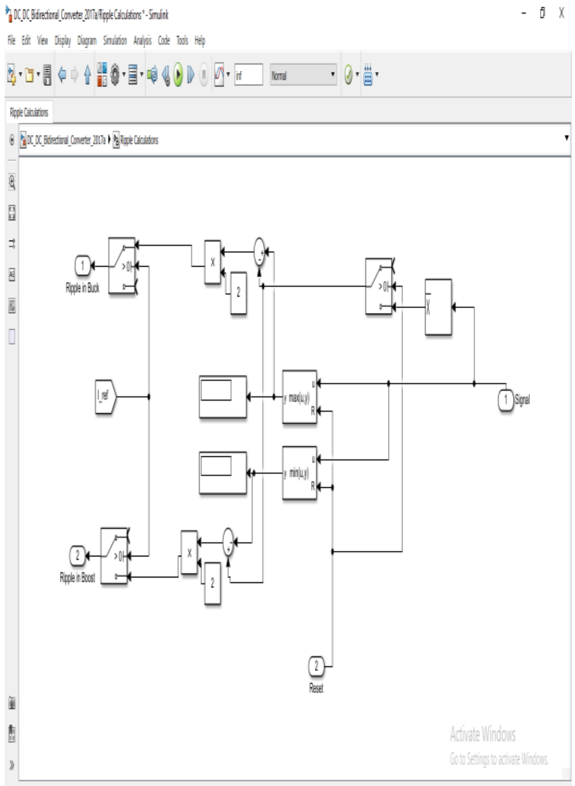


Fig.14.Ripple Calculation circuit.

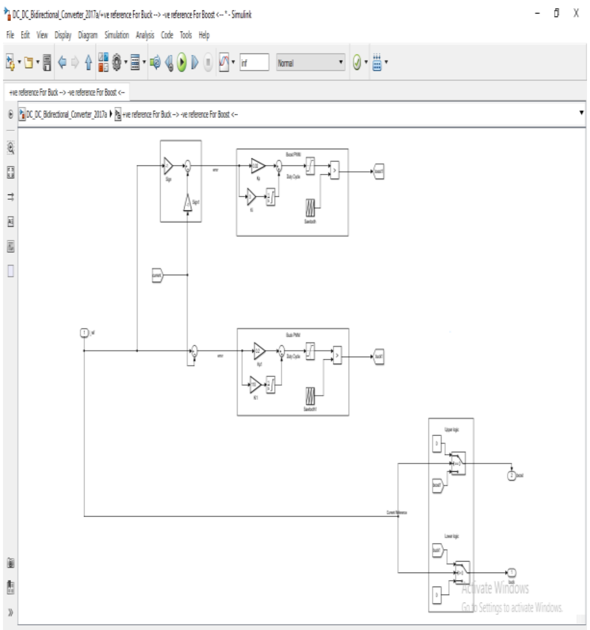


Fig.15.PI controller for the dc-dc converter.

- DC bus voltage = 300 V
- Battery Voltage = 120 V
- Battery Rating = 800 Ah
- Maximum value of ripple is 0.623.

4.2 Circuit Operation**:**

The load is shared between the battery (through the DC/DC bidirectional converter) and the DC bus.

The measurement is compared with the reference, then we get the error from the PI then translate the error to a duty cycle. For example, the measured current is 1A and the desired/ reference is 5A then the error is 4, however, the duty cycle only varies between 0 to 1, therefore, we need a translator or converter to convert this error to something between 0 and 1, which is the PI. Since we know the range of the values of the input to the PI (i.e. error) and its output (i.e. duty cycle), this might be helpful also in tuning, to figure out Kp and Ki. Once we get the duty cycle, it is just a number and the IGBT switch only understand 1 or 0, then we compare the duty cycle number with a sawtooth signal (sawtooth vary from 0 to 1) to get pulses (i.e. zeros and ones) that go to the IGBT.

The circuit is operated in two cases.
Case – 1**:** Power is supplied to the battery (battery is charging and it will take the current, so current is positive).

Case – 2: Power is supplied from the battery (battery is supplying the power, current, in this case, is negative).

4.4.1 Waveforms for Case 1

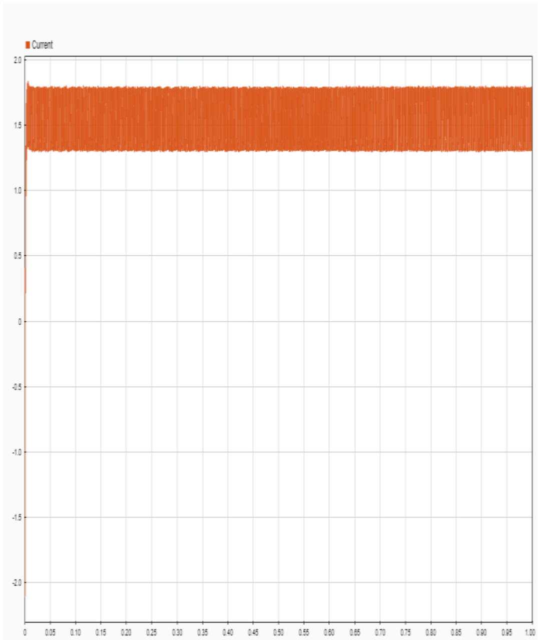


Fig.16.Current flowing into the battery (Battery is charging)

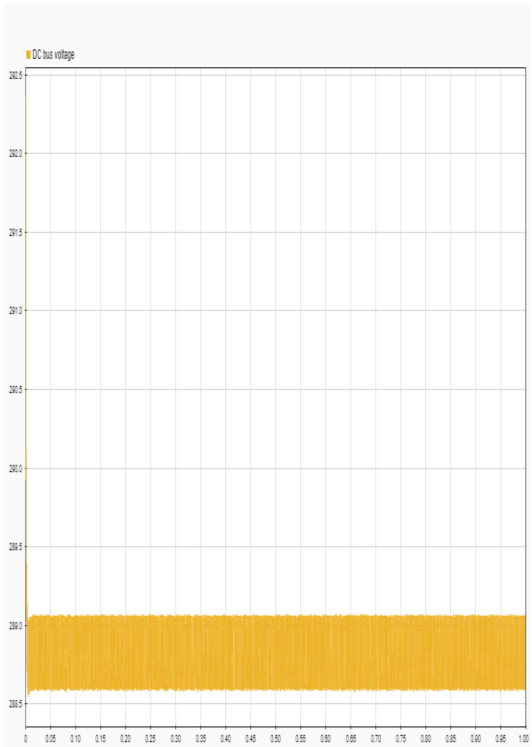


Fig.17. DC bus voltage waveform

4.4.2 Waveforms for Case 2:

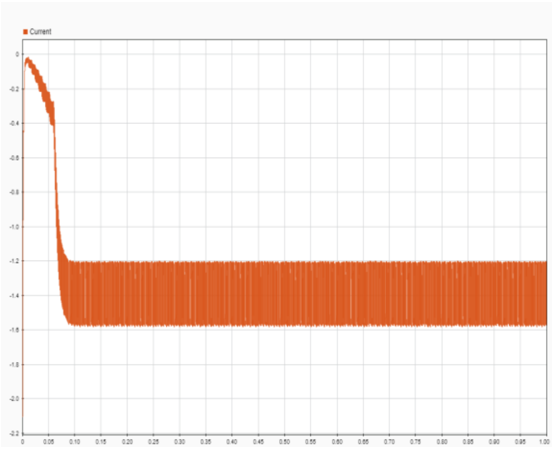


Fig.18. Current flowing out from the battery (Battery is supplying power in the reverse direction)

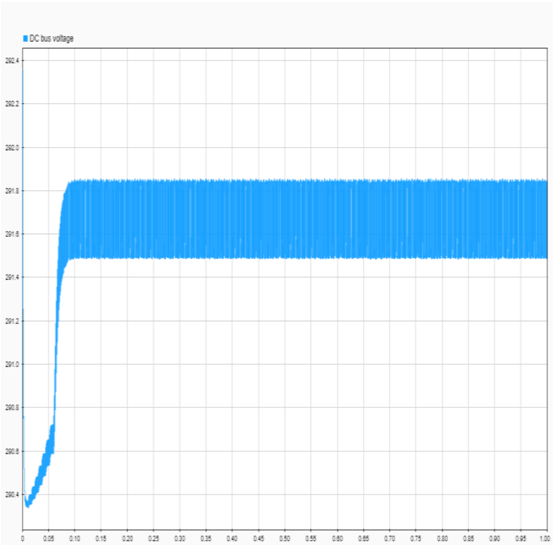


Fig.19.DC bus voltage during the case 2

From the output waveforms, it is clear that the converter designed for the power transfer is operating in bi-direction mode. The DC bus voltage is almost constant. The current is reversed by changing the reference value.

CONCLUSION

Various DC /DC converters are analyzed, which are suitable for the charging circuits of electric vehicles. The following conclusions are made from the work carried out in this thesis.

The simulation results proved that the designed bi-directional circuit can work in both directions.

The simulation results proved the back-to-back operation of the DC-DC converter (Power flow from grid to vehicle and vehicle to grid).

The provision for calculation of ripple content is given in the simulations with a maximum allowable ripple value of 0.623 %.

FUTURE SCOPE

The following aspects are left as the future scope of this work.

1. The tool used in the present work is the SIMULINK, which is having a lot of limitations. Hence, similar work can be verified using the other tools/software.
2. The core loss models presented are not very accurate due to the lack of mathematical models. Hence, these models can be found from field based studies.

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