Rectified AC Input Connected Fully Directional Universal Converter with LC Series Soft-Switching Circuit for EV, HEV & PHEV Applications

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Abstract: This paper focuses on the study of rectified ac input connected fully directional universal converter with LC series soft-switching circuit for electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). In the applications mentioned above, the proposed converter interfaces the energy storage device with motor drive. In this paper battery is used as energy storage device. Charging and discharging action of battery, during acceleration and regenerative braking of motor take place through this bidirectional dc to dc converter. That is bucking and boosting action will take place in one direction with no inverted output voltage. Rectified ac input voltage is used here for Vdc to Vbatt, bucking and boosting action. LC series resonant circuit is added with proposed bidirectional dc to dc converter for soft-switching action and closed loop PI controller is used for controlling purpose. Four modes of operation of proposed converter is described and simulations work are done in MATLAB simulink.

Keywords: Fully directional universal converter, Rectifier circuit, PI controller, LC series circuit, EV, HEV and PHEV

1. Introduction

For the requirements of reducing emissions, pollution and getting better performance, electrification in transportation industry is very essential. It also has so many advantages like electric motors are simple in construction and it also has greatest degree of energy resilience. The energy efficiency of EVs is higher than that of internal combustion engine. EVs can be plugged into the grid when not in use, that is stabilization of grid is possible. So automotive companies are interesting to develop electric vehicles, hybrid electric vehicle and plug-in hybrid electric vehicle. Power electronics concept is the enabling technology for the development of these vehicles. The proposed bidirectional dc to dc converter is used for transferring energy between different voltage levels. Electric vehicle use one or more electric motor for traction purpose, HEV use electric motor and other source for energy, but PHEV use external charger for traction purpose. The figure 1.1 shows the roll of bidirectional dc to dc converter in PHEV.

It has two modes of operations, driving mode and grid connected mode. In driving mode two cases are possible, Vdc>Vbatt and Vdc<Vbatt. In Vdc>Vbatt, the bidirectional dc to dc converter stepped up during acceleration and stepped down during braking. And in Vdc<Vbatt, the proposed converter stepped down during acceleration and stepped up during braking. Similarly in grid connected mode Vrec>Vbatt and Vrec<Vbatt are possible. In this case, Vrec>Vbatt, the converter stepped up in discharging and stepped down in charging. Similarly in Vrec<Vbatt the proposed converter stepped up in charging and stepped down in discharging. 12 pulse rectifier is used for the rectification action. Soft switching action is done through series LC circuit.

2. Bidirectional DC to DC Converter and Operating Modes

The figure 2.1 shows the schematic of the proposed bidirectional dc to dc converter. It has five power switches and five power diodes, which are properly connected to get bucking and boosting mode of operations. Vdc represents the dc link voltage and Vbatt denotes battery terminal voltage.

Figure 1.1: Bidirectional dc to dc converter in PHEV

Figure 2.1: Proposed bidirectional dc to dc converter
IGBT is used as power switches. The proposed converter is capable of operating $V_{dc}$ to $V_{batt}$ bucking, $V_{batt}$ to $V_{dc}$ bucking, $V_{batt}$ to $V_{batt}$ boosting, and $V_{batt}$ to $V_{dc}$ boosting by proper connection with positive output voltage. Operating modes are described in the table 2.1.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mode</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}$ to $V_{batt}$</td>
<td>BOOST</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>PWM</td>
</tr>
<tr>
<td>$V_{batt}$ to $V_{dc}$</td>
<td>BUCK</td>
<td>PWM</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>$V_{batt}$ to $V_{batt}$</td>
<td>BOOST</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
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</tr>
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<td>$V_{batt}$ to $V_{dc}$</td>
<td>BUCK</td>
<td>OFF</td>
<td>ON</td>
<td>PWM</td>
<td>OFF</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Here four modes of operations are possible. In each operating mode any one of the switches is operating in PWM mode and other switches are act as simple on or off. It require only one high current inductor.

**VDC TO Vbatt Boost Mode of Operation**

Here $T_5$ is operated in PWM switching mode and $T_2$ and $T_3$ remain in off state. At the same time $T_1$ and $T_4$ remain on all the time. Then boost converter is formed by $D_1 - D_3 - L - T_3 - T_5$. When $T_5$ is ON, the current from $V_{dc}$ passes through $D_1, T_1, L, T_5$. When $T_5$ is OFF, both the source and inductor currents flow to the battery side through $D_4$ and $T_4$.

**VDC TO Vbatt Buck Mode of Operation**

Here $T_1$ is operated in PWM switching mode and $T_2$ and $T_3$ remain in off state. At the same time $T_4$ and $T_5$ remain on all the time. Then buck converter is formed by $D_2 - T_2 - D_3 - L - T_2$. When $T_1$ is ON, the current from $V_{dc}$ passes through $D_1, T_1, L$. When $T_1$ is OFF, the output current is recovered by freewheeling diode $D_5$.

**VBATT TO VDC Boost Mode of Operation**

$T_5$ is operated in PWM switching mode. And $T_1$ and $T_4$ remain OFF state. Then $T_2$ and $T_3$ remain ON all the time. Boost converter is formed by $T_1 - D_2 - L - T_2 - T_3$ and $D_5$. When $T_5$ is on, the current from $V_{batt}$ passes through $T_1, D_3, L$ and $T_5$. When $T_5$ is off, both inductor and source current pass through $T_2$ and $D_2$.

**VBATT TO VDC Buck Mode of Operation**

$T_3$ is operated in PWM switching mode. And $T_1, T_4$ and $T_5$ remain OFF. Then $T_2$ remain ON all the time. Therefore Buck converter is formed by $T_3 - D_3 - L - T_2 - D_4$. When $T_3$ is on, the current from $V_{batt}$ passes through $T_3, D_3, L, T_2$ and $D_4$. When $T_3$ is off, the output current is freewheeled through the $D_5, T_2$ and $D_2$.

### 3. Soft Switching Series LC Circuit

The schematic circuit of soft switching LC resonant circuit is shown in figure 3.1.
This LC resonant circuit used for avoiding transformer in bidirectional dc to dc converter and reduce the losses during turn on and turn off time of the switches. Here \( C_s \) is the snubber capacitance, \( L_r \) is the resonance inductor and \( C_r \) is the resonance capacitor.

### 4. AC TO DC Rectifier

The schematic of 12 pulse converter is shown. Twelve pulse rectifiers are formed by the cascaded connection of two 6 pulse converter. Primary of the transformer is star connected and one of the secondary is star connected and other one is delta connected.

### 5. PI Controller

The key feature of this control is the existence of a feedback loop. Figure 5.1 shows the control system.

Furthermore, in this control scheme, the difference between the output voltages \( V_{batt} \), (dc), and a reference signal, \( V_{ref} \), is processed by a compensation network which generates an error signal, \( V_{err} \). This error signal tells how the duty cycle has to be changed in order to give the best transient dynamics for the desired output. This error signal is given as input to the PI controller. The output of PI controller is compared with a periodic ramp signal, \( V_{ramp(t)} \), to generate a pulse width modulated signal which drives the switch.

### 6. MATLAB Simulations and Results

Simulations of four modes of operations of bidirectional dc to dc converter with soft switching LC resonant circuit is done by using MATLAB Simulink. \( V_{dc} \) to \( V_{batt} \) boosting, \( V_{dc} \) to \( V_{batt} \) bucking, \( V_{batt} \) to \( V_{dc} \) boosting and \( V_{batt} \) to \( V_{dc} \) boosting circuits are shown below. Figure 6.1 represents \( V_{dc} \) to \( V_{batt} \) boosting, here \( V_{dc} \) is 24V and \( V_{batt} \) is 42V. Boost mode simulation circuit result is shown in figure 6.2. Figure 6.3 shows \( V_{dc} \) to \( V_{batt} \) bucking simulation circuit, with \( V_{dc} \) 42V and \( V_{batt} \) 24V. Figure 6.4 shows buck mode simulation circuit result. Figure 6.5 represents \( V_{batt} \) to \( V_{dc} \) boost mode simulation circuit with \( V_{batt} \) 24V and \( V_{dc} \) 42V. Figure 6.6 represents boost mode simulation circuit result. Figure 6.7 represents \( V_{batt} \) to \( V_{dc} \) buck simulation circuit with \( V_{batt} \) 53V and \( V_{dc} \) 24V. Figure 6.8 represents buck mode simulation circuit result. First channel represents input voltage and second channel represents output voltage.
7. Conclusion

This study presents a novel dc/dc converter structure that is suitable for both industrial needs and the electric vehicle conversion approaches for all EV, HEV, and PHEVs applications. Rectified AC input connected bidirectional dc to dc converter with LC circuit soft switching is designed and simulated by using MATLAB simulink and the output of four modes of operations are recorded. This circuit works, bucking and boosting action in one direction. LC resonant soft switching circuit reduces the switching losses. These circuits are designed by using IGBT.

References


**Author Profile**

Neenu C Robin received the B-Tech degree in Electrical and Electronics Engineering from Vimal Jyothi Engineering College under Kannur University in 2012 and M.E degree in Power Electronics and Drives in Electrical Engineering from CSI collaage of Engineering, Ketti, under Anna University Chennai in 2014.